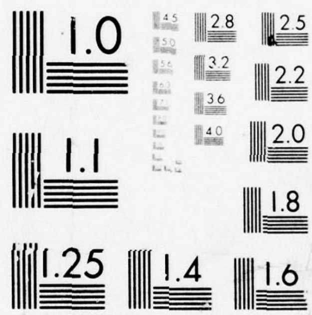
AD-A044 190   AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OHIO SCHO--ETC   F/G 1/3
A FEASIBILITY STUDY TO DEVELOP OPTIMIZATION ALGORITHMS FOR AIRC--ETC(U)
JUN 77   R L EVANS, B P CHRISTENSEN

UNCLASSIFIED   AFIT-LSSR-30-77A   NL

1 OF 2
AD
A044190


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0

AD A044190

3
B.S.

AF INSTITUTE OF TECHNOLOGY

UNITED STATES AIR FORCE

AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

(3)

(11) Jun 77

(9) Master's thesis,

(12) 130 p.

(6)

A FEASIBILITY STUDY TO DEVELOP
OPTIMIZATION ALGORITHMS FOR
AIRCRAFT STRUCTURES.

(10)

Ronald L. Evans / Major, USA
Bruce P. Christensen / Captain, USAF

(14) AFIT-LSSR-30-77A

012 250

The contents of the document are technically accurate, and no sensitive items, detrimental ideas, or deliterious information are contained therein. Furthermore, the views expressed in the document are those of the author and do not necessarily reflect the views of the School of Systems and Logistics, the Air University, the United States Air Force, or the Department of Defense.

USAF SCN 75-20B AFIT Control Number LSSR 30-77A

AFIT RESEARCH ASSESSMENT

The purpose of this questionnaire is to determine the potential for current and future applications of AFIT thesis research. Please return completed questionnaires to: AFIT/SLGR (Thesis Feedback), Wright-Patterson AFB, Ohio 45433.

1. Did this research contribute to a current Air Force project?

a. Yes b. No

2. Do you believe this research topic is significant enough that it would have been researched (or contracted) by your organization or another agency if AFIT had not researched it?

a. Yes b. No

3. The benefits of AFIT research can often be expressed by the equivalent value that your agency received by virtue of AFIT performing the research. Can you estimate what this research would have cost if it had been accomplished under contract or if it had been done in-house in terms of manpower and/or dollars?

a. Man-years ________ $ ________ (Contract).

b. Man-years ________ $ ________ (In-house).

4. Often it is not possible to attach equivalent dollar values to research, although the results of the research may, in fact, be important. Whether or not you were able to establish an equivalent value for this research (3 above), what is your estimate of its significance?

a. Highly Significant b. Significant c. Slightly Significant d. Of No Significance

5. Comments:

________________________ ________________________
Name and Grade Position

________________________ ________________________
Organization Location

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

AFIT/LSGR (LT Col Barndt)
Wright-Patterson AFB, OH 45433

AU FORM JUL 74 6

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER LSSR 30-77A	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A FEASIBILITY STUDY TO DEVELOP OPTIMIZATION ALGORITHMS FOR AIRCRAFT STRUCTURES		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Ronald L. Evans, Major, USA Bruce P. Christensen, Captain, USAF		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Graduate Education Division School of Systems and Logistics Air Force Institute of Technology, WPAFB OH		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Department of Research and Administrative Management (LSGR) AFIT/LSGR, WPAFB OH 45433		12. REPORT DATE June 1977 13. NUMBER OF PAGES 112
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

APPROVED FOR PUBLIC RELEASE AFR 190-17.

JERRAL F. GUESS, CAPT, USAF
Director of Information

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Cost Estimation
Aircraft Structural Design
Parametric Studies on Aircraft Structural Design
Design to Cost
Acquisition

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Thesis Chairman: Leslie J. Zambo, Major, USAF

The concept of design to cost requires accurate cost estimation throughout the acquisition process of a major weapon system. Cost estimation is particularly important during the conceptual and validation phases. This research effort was directed toward improving cost estimation techniques for aircraft structures. Previous cost estimates had been derived through the use of a Vehicle Design and Evaluation Program (VDEP) which designed an aircraft structure to a minimum weight for a given set of structural parameters. However, a vehicle designed for minimum weight did not necessarily result in a structure with the lowest cost. This study examined the feasibility of developing algorithms which would, together with VDEP, design a cost optimized airframe structure. Cost as the dependent variable was regressed with load factor, rib spacing, structural types, skin thickness, and weight as the independent variables. The results of the research showed that it is feasible to develop cost optimization algorithms by using the highly significant relationship between skin thickness and rib spacing. The analysis further indicated that when weight was removed from the regression model, skin thickness became the key design parameter.

LSSR 30-77A

A FEASIBILITY STUDY TO DEVELOP OPTIMIZATION ALGORITHMS FOR AIRCRAFT STRUCTURES

A Thesis

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Logistics Management

By

Ronald L. Evans, BA
Major, USA

Bruce P. Christensen, BS
Captain, USAF

June 1977

Approved for public release;
distribution unlimited

This thesis, written by

Major Ronald L. Evans

and

Captain Bruce P. Christensen

has been accepted by the undersigned on behalf of the faculty of the School of Systems and Logistics in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN LOGISTICS MANAGEMENT

DATE: 15 June 1977

Leslie J Zambo

COMMITTEE CHAIRMAN

ACKNOWLEDGMENTS

The authors express sincere appreciation to their faculty advisor, Major Leslie Zambo, for his assistance and guidance throughout the conduct of this research project. A special debt of gratitude is extended to the personnel of the Preliminary Design Group, Structures Division, USAF Flight Dynamics Laboratory for identifying the need to develop effective cost optimization algorithms and for their support of this project. Mr. Cecil Wallace, Chief of the Preliminary Design Group was especially helpful in sponsoring the project and allowing his staff to be available to assist in the study. The authors thank Mr. Manaul Talley and Mr. Dale Nelson of the Preliminary Design Group staff for the many hours they spent explaining the detailed aspects of aircraft structural design and for their technical expertise which proved invaluable to the study effort. Thanks goes to Mr. Richard Sower, of the Directorate of Data Automation, AFIT/LSC, for his support and cooperation in using the CALCOMP plotter graphics package. A special thank you goes to Ms. Joyce Clark for her professional assistance in typing the numerous drafts and the final thesis. Last, but certainly not least, the authors express deep appreciation to their wives, Karen and Lorna,

for their patience, understanding, and unwavering support throughout the graduate year at AFIT.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS AND ACRONYMS

ASD	Aeronautical Systems Division
C	Cost
CALCOMP	California Computing Corporation
CDC	Control Data Corporation
CG	Center of Gravity
CREATE	Computational Resources for Engineering and Simulation, Training and Education
d.f.	Degrees of Freedom
DOD	Department of Defense
DTC	Design to Cost
EV	Explained Variation
F_c	Critical F Value
F_o	Computed F Statistic
H_o	Null Hypothesis
H_1	Alternate Hypothesis
L1	Integral Blade
L3	Integral Zee
L4	Integral Tee
L5	Separate Jay
MLR	Multiple Linear Regression

NASA	National Aeronautics and Space Administration
P	Probability
R	Rib Spacing
R^2	Coefficient of Determination
RDT&E	Research, Development, Test, and Evaluation
SPSS	Statistical Package for the Social Sciences
SSE	Sum of Squares Error
SSR	Sum of Squares Regression
SST	Sum of Squares Total
T-bar ($\bar{T}$)	Average Thickness of Wing Skin
TPP	Total Package Procurement
TV	Total Variation
U	Load Factor
USAFFDL	U.S. Air Force Flight Dynamics Laboratory
UV	Unexplained Variation
VDEP	Vehicle Design Evaluation Program
W	Weight

CHAPTER I

INTRODUCTION

PROBLEM STATEMENT

This research effort encompassed an area in need of study that had been identified by the U.S. Air Force Flight Dynamics Laboratory (AFFDL) at Wright-Patterson AFB, Ohio. The AFFDL Structures Division is responsible for obtaining structural cost estimating data which is used in the development of aircraft design to cost estimates. Cost data is currently obtained from a computer program which designs an aircraft structure subject to a minimum weight routine. Since minimum weight design does not inherently result in an optimum cost design, the current program routine may produce excessive cost estimates. In order to upgrade the existing structural design and analysis computer program, a feasibility study was needed to determine whether a series of design algorithms could be developed which would perform an optimum tradeoff between minimum cost and minimum weight (11; 13; 19).

BACKGROUND

During the mid 1960s, the Department of Defense (DOD) utilized a total package procurement (TPP) policy for major weapon system acquisitions. This procurement policy called for a single point decision strategy (10:4). Industry was awarded a contract to design, develop, and produce a weapon system for a fixed price. Under TPP, the cost parameter was often obfuscated by the syndrome of "nothing but the best." The TPP policy was eventually undermined by high costs, unprecedented inflationary trends, the Vietnam war, and schedule risks (5:60). In 1968, primarily as a result of excessive cost overruns, Deputy Secretary of Defense David Packard initiated a major study effort in the area of defense materiel acquisition to examine current policy and make recommendations for improvement (2). From this study, the impetus emerged for a complete revision of DOD acquisition policy. The revision culminated in the publication of DOD Directive 5000.1 in July 1971 which formalized the procedures for acquisition of major defense systems and established cost as a co-equal to design specifications and system performance (23:4). Specifically the directive required that:

> Cost parameters shall be established which consider the cost of acquisition and ownership; discrete cost elements (e.g., unit production cost, operating and support cost) shall be translated into "design to" requirements.

System development shall be continuously evaluated against these requirements with the same rigor as that applied to technical requirements [23:4].

The concept of design to cost (DTC) was embraced by DOD in order to use unit cost goals as thresholds for managers and as design parameters for engineers (22:4). The DTC process was formalized in 1971 by the publication of DOD Directive 5000.28. This directive established the framework for DTC whereby DTC goals would prevent funds from being spent beyond the point where costs rise rapidly for small increments of increased performance. However, minimum performance requirements were not to be sacrificed (22:4).

Experience to date indicates the objectives of DTC have not been met and cost growth in DOD major weapon system acquisitions continues to be a problem (19). Past practices in the acquisition process are continually being examined to determine whether they are still needed or require modification (4:1). A study of 45 weapon system cost overruns conducted by the Comptroller General in 1973 revealed a cost growth of $19.1 billion over development estimates of $93.6 billion. Analysis indicated three major causes for this dramatic growth of costs: improved weapon capability, requirements change, and inadequate cost estimating ability (6:23-4). In the U.S. Air Force A-10A close-air support aircraft development program, the DTC goal grew from $1.524 million in 1973 to $2.215 million in

June 1976. Twenty-two percent of this cost increase, \$.151 million, was attributed to errors in estimating the original goal (12). Based on production of 729 aircraft, this would amount to \$110 million (1:26).

If DTC is to remain viable, improved techniques for estimating costs must be developed to insure DTC goals are set realistically and represent the best tradeoff possible between cost and performance (19). These methods must be applied early in the conceptual phase of the weapon system acquisition process. Analysis of cost estimating techniques performed on the F-16 air combat fighter and the avionics system of the B-1 bomber has indicated significant cost reductions can be achieved by applying detailed cost study methods during the early stages of the conceptual phase. In the F-16 program, a cost savings of over \$2.5 billion was achieved by making several relatively simple configuration changes (19). The Boeing Aerospace Company cost studies increased the research, development, test, and evaluation (RDT&E) costs of the B-1 avionics system by \$5.4 million. However, there was a reduction from estimated production costs of \$105.7 million (20:13). These savings, in the form of cost avoidance, were the direct result of early cost studies (19). Results of the F-16 and B-1 studies indicate that savings can be achieved through more accurate cost estimating techniques.

To assist AFFDL Structures Division in improving their cost estimating capability, the Vehicle Design and Evaluation

Program (VDEP) was implemented in 1975 (see Appendix B). VDEP was developed by General Dynamics Convair Aerospace Division under contract to the National Aeronautics and Space Administration (NASA) to aid in the preliminary design of aerospace structures. The program provides a vehicle synthesis capability that includes vehicle sizing, structural analysis, and cost evaluation (16:1).

The cost evaluation portion of VDEP is driven by optimization routines that attempt to design a minimum weight airframe. It provides no automated search or optimization routines that attempt to design structures at minimum cost. The cost of a particular aircraft design can be estimated by using the program, but it is not known whether a minimum cost design has been obtained (19).

A unique feature of VDEP is an interactive systems package which allows dynamic change of program input, thereby enabling the designer to perform tradeoff studies using various structural variables. While this capability has potential for improving cost estimation, it is complicated by the fact that there are more than 360,000 possible variable combinations (see Figure 1), which can be input. Since each combination of variables costs $11.35 to run through VDEP, this amounts to more than $4.1 million to obtain cost estimates with no guarantee that the results will be cost effective (19). The complexity of the interactive systems package and the high cost implications of such an approach emphasize the need for algorithms

MATERIALS

- Glass Epoxy
- Graphite Epoxy
- Boron Epoxy
- Boron Aluminum
- Aluminum
- Titanium
- Steel

FABRICATION PROCESS

- Material
  - Removal
  - Lathe
  - Drilling
  - Milling
  - Finishing
  - Chemical
- Material
  - Forming
  - Brake
- Material
  - Buildup
  - Layup
  - Laminating
  - Curing

STRUCTURAL CONCEPTS

- Honeycomb
- Sine Wave
- Integral
  - Blade
  - Tee
- Non-Integral
  - Hat
  - Vee
  - Y
  - Tee
  - Zee
  - Angle
  - Truss
  - Isogrid

COMPONENT ASSEMBLIES

- Wing
  - Primary structure
  - Secondary structure
- Tail
  - Horizontal
  - Vertical
- Fuselage
  - Shell
  - Doors
  - Mounts
  - Floors
  - Bulkheads
  - Fuel Cells

PRODUCT FORM

- Plate
- Sheet
- Bar
- Tube
- Tape
- Cloth
- Forging
- Casting
- Plastics
- Bearings
- Extrusion

[INPUT]

- Time
  - Labor Rate
  - Material Cost
- Units
  - Labor Hours
  - Material Usage
- Geometry
  - Size
  - Shape
  - Area
  - Length
  - Spacing
- Weight
  - Material cost
- Optimality

ASSEMBLY PROCESS

- Fastening
  - Bolts
  - Rivets
- Welding
- Brazing
- Bonding
- Weldbond
- Painting
- Sealing
- Bearings

PART SUBASSEMBLIES

- Covers
- Stringers
- Spar Cap
- Rib Cap
- Rib Web
- Bulkheads
- Fuselage
  - Skin
  - Stringer
  - Longeron
  - Frames
  - Bulkheads
  - Doors
  - Floors
- Mechanical
  - Hinges

[OUTPUT]

- Number of Pieces
- Weight
- Standard Hours
- Labor Hours
- Overhead
- Material Cost
- Total Manufacturing
- Tooling
- Engineering
- RTD
- Acquisition
- Operation

Figure 1. Structural Design Variables (Adapted from cost matrix model by M. E. Talley (19)).

to assist structural design engineers in developing a minimum cost design.

SCOPE

The task of accomplishing a feasibility study and developing algorithms has been estimated to require approximately two man-years, exclusive of reporting time, and over $100,000 in computer costs (19). This research effort could not accomplish the complete task within available time and resource constraints. Therefore, it was conducted to determine whether the development of such algorithms was feasible for use with VDEP. The results provide a foundation for future research work in the development of algorithms to assist in achieving minimum cost designs.

OBJECTIVE

The objective of this research effort was to determine, through a feasibility study and computer simulation, whether structural design cost optimization algorithms could be developed.

RESEARCH QUESTIONS

To accomplish the research objective, this study addressed the following questions:

1. Which variables or variable combinations should be used as primary inputs for developing algorithms?

2. Among the selected variables, what relationships exist for developing algorithms?

3. Can algorithms be developed for use in VDEP to produce an optimum cost aircraft structure design?

CHAPTER II

METHODOLOGY

DATA COLLECTION

Data Source

The data necessary for conducting the feasibility study was generated by the CDC 6600 computer system located at the Aeronautical Systems Division (ASD), Wright-Patterson AFB, Ohio. The computer, together with the VDEP software package, provided an aircraft design capability which was used to study the effects of selected variables on aircraft cost and weight. (See Appendix B for a detailed discussion of VDEP).

In conjunction with VDEP, the DC-10 data base was selected for the following reasons:

1. Currency. The DC-10 information represented the most current data package available for use with VDEP (13).

2. Accuracy. Data could be readily compared with an operational vehicle (13).

3. Relevancy. The DC-10 is among several aircraft currently being considered as an Air Force Advanced Tanker-Cargo Aircraft (17).

Universe

The universe for data collection was the DC-10 aircraft.

Population

The population was the wing structure of the DC-10. (See Appendix A for operational definitions of wing and structural variables.)

Samples

The samples consisted of a series of random observations of cost and weight based on the average thickness of wing skin (T-bar), material type, structural type, load factor, and rib spacing. Figure 2 depicts the wing structural concepts.

Variables

The variables selected for generating sample observations were the result of recommendations made by personnel of the AFFDL Structures Division (19). Wing structural variables selected for use in the study were integral blade (L1), integral zee (L3), integral tee (L4), and separate jay (L5). (See Figure 2.) The material used was aluminum (19). The structural variables along with T-bar (T), weight (W), rib spacing (R), and load factor (U), comprised the independent variables. The dependent variable was the total cost of the DC-10 wing including the costs associated with tooling,

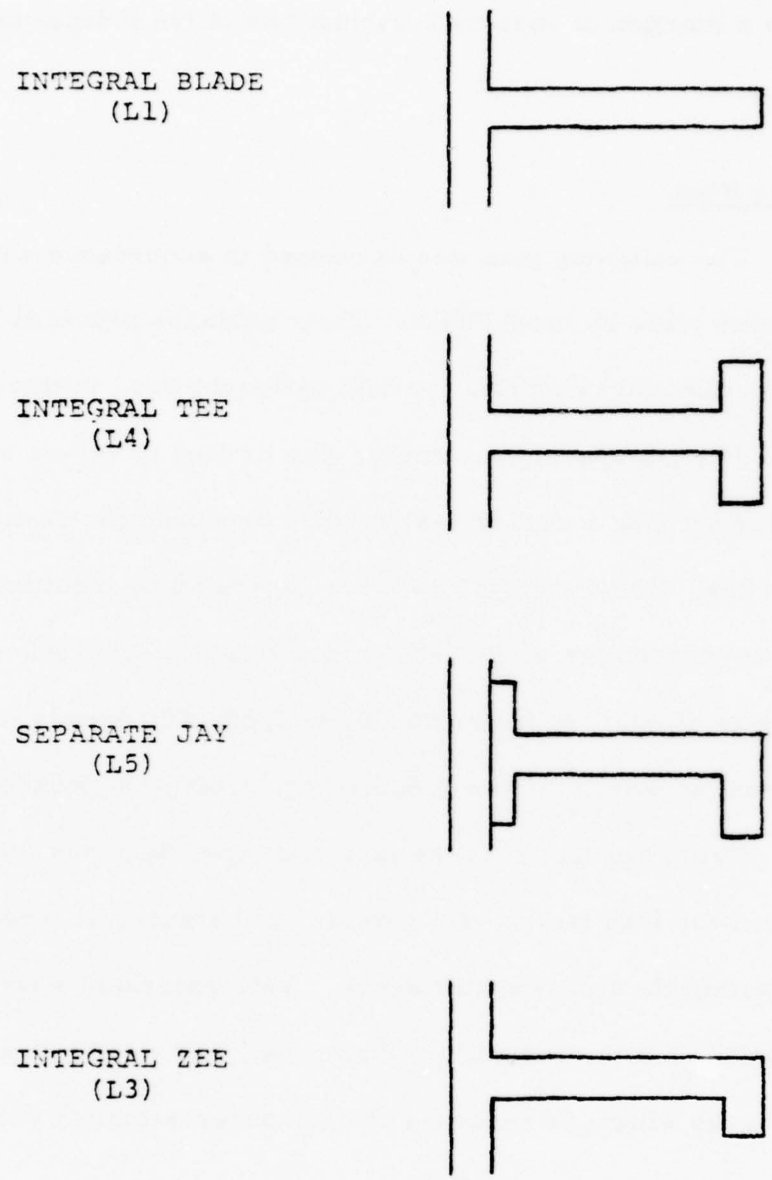


Figure 2. Aircraft Wing Structural Concepts

manufacturing, overhead, and material acquisition. Cost was computed as a function of various combinations of the independent variables.

Sampling Plan

The sampling plan was developed in accordance with recommendations made by the AFFDL. Their guidance provided the variable selection and priorities for data gathering used in this research effort. The rib spacing parameter was limited to values between 26 and 76 inches with a cost of design being produced for each increment of 10 inches. The T-bar values were generated by inputting load factors in increments of 100,000 from 300,000 to 600,000 pounds; increments of 200,000 from 600,000 to 1,800,000 pounds; and increments of 600,000 from 1,800,000 to 3,600,000 pounds (19).

Using aluminum as the material type, data was collected as the values for load factor, rib spacing, and structural types were varied within the limits stated above. This generated a total of 312 observations for the resultant T-bar, cost, and weight data. The weight of the wing was recorded at each observation for subsequent cost versus weight analysis.

STATISTICAL ANALYSIS

Multiple Linear Regression

Multiple Linear Regression (MLR) analysis provides a

highly useful analytical method for experimental situations where the experimenter is able to exercise control over the independent variables (14:215). Due to the nature of the data that was collected, MLR was the appropriate statistical model to be applied to determine whether there was a relationship between cost and the independent variables, T-bar, structural type, load factor, rib spacing, and weight. (See Appendix C for a complete description of this statistical analysis technique.)

Partial Correlation

This statistical technique was used to determine whether spurious correlations existed among the variables.

> Spurious correlation is defined in a relationship between two variables, A and B for example, in which A's correlation with B is solely the result of the fact that A varies along with some other variable, C for example, which is indeed the true predictor of B. In this case, when the effects of C are controlled, held constant, etc., B no longer varies with A [15:303].

If the fixing of one variable reduces the correlation between two variables, then it is inferred that their interdependency arose in part through the agency of the control variable and if the partial correlation was zero or very small, it is inferred their interdependence is entirely attributed to the fixed variable. If the controlled partial correlation is greater than the original correlation, then it can be inferred that the controlled variable is masking the true relationship (7:317).

CRITERIA TEST

The results of the statistical hypothesis tests on the MLR model were used to indicate which individual variables provided statistically significant net or marginal contributions to the explanatory power of the MLR model. Only significant independent variables were retained in the model since these variables exhibited the greatest impact on cost, the dependent variable. The retained variables and their relationships, as specified by the model, formed the basis for determining whether algorithms could be developed for use with VDEP to derive minimum cost aircraft structural designs.

ASSUMPTIONS AND LIMITATIONS

Assumptions

1. VDEP equations and algorithms were accurate and provided accurate data based on the selected inputs.

2. Performance specification data used to initialize VDEP were accurate.

3. Performance criteria were not exceeded in generating cost and weight data.

4. Material cost data used to initialize VDEP were accurate.

Limitations

1. The study was conducted using cost figures in 1971 dollars. Therefore, the conclusions must be viewed accordingly. Any extrapolation to other year dollars without the use of appropriate financial techniques will be in error.

2. VDEP was initialized to provide cost and weight data for the 200th aircraft structure. Generalizations drawn to a structure other than the 200th one will not be valid.

CHAPTER III

DATA ANALYSIS

INTRODUCTION

In this chapter the results of MLR are analyzed, as well as the results obtained from partial correlation. Cost was regressed with all independent variables: weight (W), rib spacing (R), load factor (U), T-bar (T), and structural types (Li). The material type used was aluminum (I5). Structural types were integral blade (L1), integral zee (L3), integral tee (L4), and separate jay (L5). Integral tee was encoded as a dummy control variable and therefore did not appear in the cost equations.

Only the statistically significant independent variables were retained from the initial MLR. Cost was then regressed with these significant variables to obtain a new model for further analysis.

The next portion of the chapter deals with the MLR of cost with the selected independent variables weight, T-bar, and structural types on an individual basis. Results from these regressions are analyzed for significance. The MLR of cost with all independent variables except T-bar and again with all but weight are examined to

determine what, if any, effect these two excluded variables have on the overall regression.

Analysis of the results obtained from the regression of cost with all significant independent variables and cost with selected variables pointed out interrelationships which necessitated the use of partial correlation. The results of the partial correlation runs are presented and explained.

The final section of the chapter examines the results obtained from plotting cost with weight and cost with T-bar for all other independent variable combinations. These graphs depict the effects of weight and T-bar on cost, and the point at which the least cost is found for each variable combination.

REGRESSION ANALYSIS

Cost with All Independent Variables

The results of MLR for cost with all independent variables are shown in Table I. The variables entered the regression equation using the forward inclusion scheme. The following hypothesis test for the overall regression was performed,

$H_o:R^2 = 0$

$H_1:R^2 \neq 0.$

Computed F (F_o) was obtained using p-1 (7) upper and n-p (304) lower degrees of freedom (d.f.). F_o = 3428.18, therefore

Table I
Multiple Regression, Cost with All Independent Variables

Variable	Name	B_i	F_o
W	Weight	82.03	506.07 *
R	Rib Spacing	-18115.82	491.71 *
L1	Integral Blade	-245121.52	21.39 *
U	Load	-0.48	4.80 **
T	T-bar	537113.71	2.89
L5	Separate Jay	-35105.52	0.84
L3	Integral Zee	-6063.52	0.03
Constant	--	2559270.88	--

* Significant at $\alpha = 0.01$

** Significant at $\alpha = 0.35$

$$\text{Cost} = 2559270.88 + 82.03\,W - 18115.82\,R - 245121.52\,L1 - 0.48U + 537113.71\,T - 35105.85\,L5 - 6063.52\,L3$$

Total Variation (TV) $= 125.12 \times 10^{13}$
Explained Variation (EV) $= 123.55 \times 10^{13}$
Unexplained Variation (UV) $= 1.57 \times 10^{13}$

$R^2 = 0.9875$

Regression $F_o = 3428.18$

$P(F \geq F_o)$ was less than 0.001. Since the F value computed was highly significant, the null hypothesis (H_o) was rejected. The conclusion was that R^2 does not equal zero statistically. Therefore, at least one B_iX_i was significant, i.e., at least one independent variable had a relationship to cost. Further hypothesis tests were conducted on the B_i regression coefficients. The hypothesis test on the net or

marginal contribution of X_i was:

$$H_o:B_i = 0$$

$$H_1:B_i \neq 0.$$

Using the conservative Bonferroni technique, an equivalent α-level was computed:

$$\text{equivalent } \alpha = \frac{\alpha}{K+1}, \text{ where } K = \text{other independent variables}$$

in the model. To obtain the F_c for a given equivalent α-level, it was necessary to use the Wonnacott and Wonnacott technique of interpolation (26:600). Comparing the individual B_i F statistic to the interpolated F_c; T-bar (T), integral zee (L3), separate jay (L5), and load (U) were found to be insignificant at $\alpha \leq 0.01$.

Cost with Significant Variables

Table II shows the results obtained from regressing cost with the significant variables. The hypothesis test for R^2 was conducted and the null hypothesis was rejected at all levels of $\alpha \geq 0.001$. Similarly, all variables' B_iX_i were found to be significant for $\alpha \geq 0.01$, using the equivalent α technique.

Cost with Selected Variables

Table III reflects the results of regressing cost with selected independent variables. In both the regression of cost with weight and cost with T-bar, the models were highly significant. However, when cost was regressed with the structural types, L5 (separate jay) had

Table II
Multiple Regression, Cost with All Significant Independent Variables

Variable	Name	B_i	F_o
W	Weight	78.72	22648.06
R	Rib Spacing	-17870.38	560.32
L1	Integral Blade	-194940.94	37.78
Constant	--	2515130.22	--

Cost = 2515130.22 + 78.72 W - 17870.38R - 194940.94 L1

TV = 125.12×10^{13}
EV = 123.52×10^{13}
UV = 1.60×10^{13}

$R^2 = 0.9872$

Regression $F_o = 7945.48$

an insufficient tolerance-level and did not enter the model. From the foregoing analysis, it was concluded that structural type (Li) taken alone is not a significant contributor to cost.

Cost with All Variables Except T-bar/Weight

Table IV depicts the results of regressing cost with all independent variables except T-bar. No unexpected relationships were found. The overall regression was significant at $\alpha \geq 0.001$.

Table V shows the results of regressing cost with all independent variables except weight. The overall regression was significant. Load (U) entered the equation first since it had the greatest

Table III
Multiple Regression, Cost with Selected Independent Variables

Cost with Weight

$$Cost = 1552546.82 + 78.52\ W$$

$TV = 125.11 \times 10^{13}$ $\qquad R^2 = 0.9624$
$EV = 120.41 \times 10^{13}$
$UV = 4.70 \times 10^{13}$ $\qquad F_o = 7936.82$

Cost with T-bar

$$Cost = 1827310.07 + 2592502.69\ T$$

$TV = 125.11 \times 10^{13}$ $\qquad R^2 = 0.9117$
$EV = 114.06 \times 10^{13}$
$UV = 11.05 \times 10^{13}$ $\qquad F_o = 3199.77$

Cost with Structural Types

Variable	Name	B_i	F_o
L1	Integral Blade	593523.65	4.17
L3	Integral Zee	-82435.24	0.08
	Constant	4524667.68	

Note: L5 had insufficient tolerance-level to be included in the regression with an $F_o = 0.005$.

$TV = 125.11 \times 10^{13}$ $\qquad R^2 = 0.0166$
$EV = 2.08 \times 10^{13}$
$UV = 123.03 \times 10^{13}$ $\qquad F_o = 2.61$

Table IV
Multiple Regression, Cost with All Independent Variables Less T-bar

Variable	Name	B_i	F_o
W	Weight	84.18	602.51
R	Rib Spacing	-17635.20	526.21
L1	Integral Blade	-263038.85	25.49
U	Load	-0.14	2.60
L5	Separate Jay	-29905.29	0.61
L3	Integral Zee	-4385.13	0.01
Constant	--	2522902.36	--

$$\text{Cost} = 2522902.36 + 84.18\ W - 17635.20\ R - 263038.85\ L1 - 0.14\ U - 29905.29\ L5 - 4385.13\ L3$$

$TV = 125.11 \times 10^{13}$
$EV = 123.53 \times 10^{13}$
$UV = 1.58 \times 10^{13}$

$R^2 = 0.9874$

$F_o = 3974.49$

explanatory power. As rib spacing (R) and integral blade (L1) entered, the significance of U increased as evidenced by the increasing F_o for the coefficient of U. However, the computed F-value for U dropped from 3250.54 to 0.81 when T-bar entered the model. This drop in significance was attributed to the high correlation (value of r) between U and T-bar. This relationship was further examined using partial correlation techniques.

Table V
Multiple Regression, Cost with All Independent Variables Less Weight

Variable	Name	B_i	F_o
U	Load	-0.30	0.72
R	Rib Spacing	-23430.47	337.95
L1	Integral Blade	580850.26	86.94
T	T-bar	3009457.51	38.80
L3	Integral Zee	-70973.52	1.30
L5	Separate Jay	-14063.94	0.05
Constant		2872221.05	

$$\text{Cost} = 287221.05 - 0.3\ U - 23430.47\ R + 580840.26\ L1 - 3009457.51\ T - 70973.52\ L3 - 14063.94\ L5$$

$TV = 125.11 \times 10^{13}$ $\qquad R^2 = 0.9667$
$EV = 120.94 \times 10^{13}$
$UV = 4.17 \times 10^{13}$ $\qquad F_o = 1474.11$

Step	Variable	F_o	R^2
1	U	3250.54	0.9129
2	U	5204.64	0.9458
	R	187.36	
3	U	7429.75	0.9622
	R	267.46	
	L1	133.11	
4	U	0.81	0.9665
	R	339.29	
	L1	144.02	
	T	39.89	

PARTIAL CORRELATION

To unmask any hidden relationships between or among independent variables, the partial correlation package in the SPSS program was used. Through the use of partial correlation, it was possible to examine the effects of multi-collinearity. Zero, first, and second order partial correlation coefficients were obtained for cost and each of the independent variables. In each run, weight and T-bar were the variables that had the most significant effect on each of the other independent variables. When weight and T-bar were controlled, some coefficients which had previously been negative became positive and some positives became negative (see Appendix D). This effect was also noted in the relationship between T-bar and weight where each in the presence of the other had a significant change in partial correlation. For example, T-bar dropped from 0.95 to -0.02 when weight was controlled and weight dropped from 0.98 to 0.76 when T-bar was controlled. The large drop in the partial correlation coefficient of T-bar accounts for the seemingly paradoxical relationship obtained when cost was regressed with all independent variables as opposed to cost regressed with T-bar alone.

Partial correlation also explained the relationship of T-bar and load (U) which was uncovered when cost was regressed with all variables except weight. Recall that U showed a high degree of significance until T-bar entered the equation. The zero order partial

for U with T-bar was 0.9981 which explained the effect T-bar had on U. The zero order partial for cost with U was 0.9555; however, when the first order partial was taken, the coefficient for cost with U became 0.1349 when in the presence of T-bar. This was a significant drop in partial correlation and accounts for the extreme drop in the F-value for U when T-bar entered the regression model. Appendix D contains a graphic presentation of selected partial correlation coefficients.

GRAPHIC ANALYSIS

In order to further analyze the relationships of cost with weight and T-bar, it was necessary to plot the cost to T-bar and cost to weight relationships. These graphs were generated on CREATE using the CALCOMP Plotter (see Appendix E for selected graphs). All plots were obtained for a given rib spacing and structural type over the complete range of load factors. This provided twenty-four individual graphs for weight and twenty-four for T-bar. To make the plots more meaningful and easier to interpret, the plots were drawn with 100 points instead of the observed thirteen data points. Hence, there was some computer interpolation between the observed data points.

The graphs of cost and T-bar depict three significant relationships. First, the lowest cost occurs in a T-bar range of 0.25 to 0.50

inches. Second, T-bar and cost exhibit a linear relationship when T-bar ranges from 0.5 to 3.0 inches. For T-bar readings less than 0.5 inches, there is a non-linear (parabolic) relationship. The third relationship deals with the structural variables. The separate jay consistently exhibits the lowest cost and integral blade the greatest cost. Integral tee and integral zee have the same values and are, in terms of cost, greater than the separate jay and less than integral blade. This third relationship holds true for all rib spacings (26 to 76 inches). It also holds for all T-bar values except in the 0.25 to 0.50 range.

Selected graphs of cost with weight are included in Appendix E for comparison with the cost with T-bar graphs since previous research stressed the significance of the cost-weight relationship (9:2-10).

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

INTRODUCTION

This chapter presents the conclusions and recommendations resulting from the research effort. The conclusions associated with the research questions are presented first. They are followed by corollary conclusions that were developed in addition to the central research objective. A brief summary of the study is presented and then recommendations for future associated research close the chapter.

CONCLUSIONS

The major thrust of this research effort was to determine the feasibility of developing algorithms for use with VDEP to optimize the cost estimation of aircraft structures. While the precise nature of these algorithmic equations was not ascertained, a significant degree of insight was gained which showed the feasibility of such algorithms. The research findings provide the necessary vehicle for developing specific cost optimization algorithms. The conclusions

drawn from this study are presented in the same order as the research questions outlined in Chapter I.

1. Based on the statistical significance of the R^2 value obtained through MLR, some relationship does exist between the independent variables and cost. Variables found to be the most significant were weight, rib spacing, and integral blade. However, when weight was deleted, skin thickness (T-bar) took over as the key design parameter. Weight was not an input design parameter, but the result of a fallout from the input parameters (19). Hence, the net effect is the addition of two design parameters, T-bar and rib spacing, to a suggested list of key cost drivers (9:2-10). With these design parameters the cost analysts will be able to perform sensitivity analysis and make recommendations to the design engineers on ways to search for a least cost structure.

2. The relationships of load, T-bar, rib spacing, and cost are best depicted in the graphs contained in Appendix E. Based on data collected for the research effort, there exists a strong case for linearity. However, the graphs indicate that this may not be the best interpretation. The relationship shows signs of a much higher order which could be curvelinear. Therefore, a power function may best reveal the relationship between T-bar and cost.

It is imperative to understand that a given T-bar and rib spacing are two primary factors which determine weight. Hence, the

relationship between T-bar and rib spacing is an essential element in the development of a successful cost optimization algorithm.

3. Based on the statistical analysis of the data as explained in Chapter III, the researchers believe that algorithms can be developed which will, together with VDEP, assist design engineers, cost analysts, and program planners in designing and selecting an optimum cost aircraft structural design. The principle result will be to strengthen the credibility of cost estimations which are vital to the viability of the overall design to cost concept.

COROLLARY CONCLUSIONS

The corollary conclusions are further results of the basic research effort. Although they were incidental to the primary thrust of answering the research questions, they add a great deal of value to the original intent of the study.

1. There exists some value of T-bar beyond which it is not feasible to search for an optimum cost. As T-bar reaches a value of approximately one inch, the weight of the aircraft increases at an increasing rate. This increase would require the size of the aircraft to be scaled upward, or alternatively, a reduction in structural performance, or some combination thereof.

2. Among the 312 data values, minimum cost occurred when T-bar was in the range of 0.25 to 0.50 inches. (See Appendix E).

3. The structural type selected was an insignificant factor in determining cost. However, in the presence of T-bar, the integral blade became an important factor in the regression model and was significant in its relationship to cost. When comparing the graphs for the various structural types, it became evident that the integral blade consistently produced a higher cost for a given value of T-bar.

4. As a general rule, when rib spacing increased, cost decreased while holding the structural type constant. This relationship is depicted in the T-bar and cost graphs and leads to the conclusion that a wing with a 56 inch rib spacing can be produced for less cost than one with a 26 inch rib spacing. In the past, many aircraft structures have been designed using a 10 to 20 inch rib spacing (19). This may have not been the most cost effective rib spacing. Future wing designs should consider rib spacings greater than 20 inches to see if cost can be further optimized.

SUMMARY

This research effort attempted to uncover relationships between cost and key design parameters in such a manner as to ascertain whether algorithms can be developed which will assist VDEP in designing an optimum cost aircraft structure. By using the VDEP program, it was determined that some key variables exist which have a statistically significant relationship to cost. Among the

variables examined, T-bar appeared to be the most promising input design parameter for use in developing cost optimization algorithms. Further study is recommended to prescribe the exact nature of the cost-to-T-bar relationship in order to definitize structural design algorithms.

RECOMMENDATIONS FOR FURTHER RESEARCH

1. Due to the intermixing of data points in the 0.25 to 0.50 region of T-bar, additional analysis should be made in an attempt to spread out this area and develop a better picture of what happens to cost. The area should be enlarged to include smaller values of T-bar, even as small as 0.05 inches. Further research in this area will assist in determining the exact causes of the cost fluctuations.

2. Closely related to the expanded study of T-bar is the development of a locus of points in the lower ranges of T-bar. This locus of points could be obtained by using the cost with T-bar family of graphs. By overlaying the graphs, the locus of points for lowest cost would be plotted. This locus would then enable one or more equations to be developed which would drive cost to its minimum point.

3. The models contained in this study are highly simplified since they are linear. An attempt must be made to determine whether higher order relationships exist among the variables and

what the higher order relationships are.

4. Throughout this study, rib spacing (R) was the only variable from the group of geometric variables that was taken into account. Other variables affecting wing geometry are spar spacing and stringer spacing. Therefore a closer look at the geometry involved in designing an aircraft is in order. Spar spacing or stringer spacing may take on additional significance and help the designer achieve a more realistic cost optimization design.

5. During this study, data was generated for the 200th aircraft in a production run. Further research should analyze data generated by selecting the 10th, 40th, 500th, or some other aircraft to ascertain the effect on cost.

6. Additional research should be accomplished to determine which independent variable causes weight (W) to be a fallout rather than a design parameter. Partial correlation of all independent variables with weight would assist in uncovering this relationship.

APPENDIX A

DEFINITIONS

Algorithm. "A set of procedures or logical steps necessary to calculate and modify the input data values to obtain the answers. It is the development of a logical approach to a problem [18:4]."

Conceptual phase. That phase of the weapon system acquisition process which begins with the determination of a needed operational capability.

> This phase defines and selects the system concepts which warrant further development. The conceptual phase is a highly iterative process, with activities performed simultaneously or sequentially as the bases for the acquisition are established by the procedural, fiscal, analytical, experimental, and engineering efforts accomplished at DOD [21:2. 1].

Cost (C). An amount or quantity of money which is given up (paid) to purchase the specified goal or objective. All data costs are given in 1971 dollars.

Design to cost. A management concept wherein rigorous cost goals are established during the early phases of system development. The control of system costs (acquisition, operating, and support) of these goals is achieved by practical tradeoffs between operational capability, performance, cost, and schedule. Cost, as a key design parameter, is addressed on a continuing basis and as an inherent part of the development and production process (24:2).

Design to cost goal.

> A specific cost number, in constant dollars, based upon a specified production quantity and rate, established early during system development as a management objective and design parameter for subsequent phases of the acquisition cycle [24:2].

Load (U). The amount of stress, measured in pounds, that is placed on an aircraft structure.

Multicollinearity. A condition that exists when independent variables are correlated among themselves (14:250). When multicollinearity exists, the regression coefficient of any independent variable depends on which other independent variables are included in the model.

> A regression coefficient does not reflect any inherent effect of the particular independent variable but only a marginal or partial effect, given whatever other correlated independent variables are included in the model [14:252].

Parametric. A statistical term relating to an arbitrary constant which characterizes, by each of its particular values, some particular member of a system or population (25:1638).

Performance. (1) As it applies to an aircraft, performance means a prespecified set of parameters; such as, speed, range, takeoff and landing ground roll, turn radius, etc. (2) Pertaining to aircraft structure, the ability of a given structural type and/or material type to meet structure requirements as they contribute to overall aircraft

performance characteristics (19).

Rib Spacing (R). Average distance in inches between the stiffening element for the box that is the structural load carrying member (19; 15:2-79).

Stringer spacing. Average distance between the stiffening elements for the skin cover of an aircraft wing (19; 15:2-79).

T-bar (T). Wing area spread over distance to give an average thickness of the aircraft wing skin (19; 15:2-84).

Weight (W). Measurement in pounds of the material usage to construct the final product, a DC-10 wing.

Wing. The lift producing appendage to an aircraft fuselage. It is limited to the basic wing structure by excluding wing attachments such as flaps, ailerons, engines, and landing gear.

APPENDIX B

VEHICLE DESIGN EVALUATION PROGRAM - (VDEP)

The Vehicle Design Evaluation Program (VDEP)[1] is intended to be used as a preliminary design analysis tool to enable the user to rapidly perform tradeoff studies involving fatigue, fracture, static strength, weight, and cost. The total computer program is broken down into five modules (see Figure 3), the program driver, vehicle sizing, structural synthesis, detail part definition, and cost synthesis. Output may be selected from a complete and fully detailed version or a summary version based on the input data.

The program driver calls the program modules in proper sequence and initializes variables. It is appropriately titled in that it drives the total program.

The vehicle synthesis module sizes the aircraft, performs a balance analysis, distributes the area, and displays a planform view along with other pertinent design data, such as weight statements, center of gravity (CG) data, and general geometric data. This program includes a curve plotting routine which allows the user to perform parametric tradeoff studies and obtain printouts for further evaluation. These tradeoff studies are possible at several levels of consideration. For example, weight and cost data can be

---

[1]For this research effort, VDEP was used in the batch mode. The interactive graphics package was not used. All VDEP processes described herein were essentially the same.

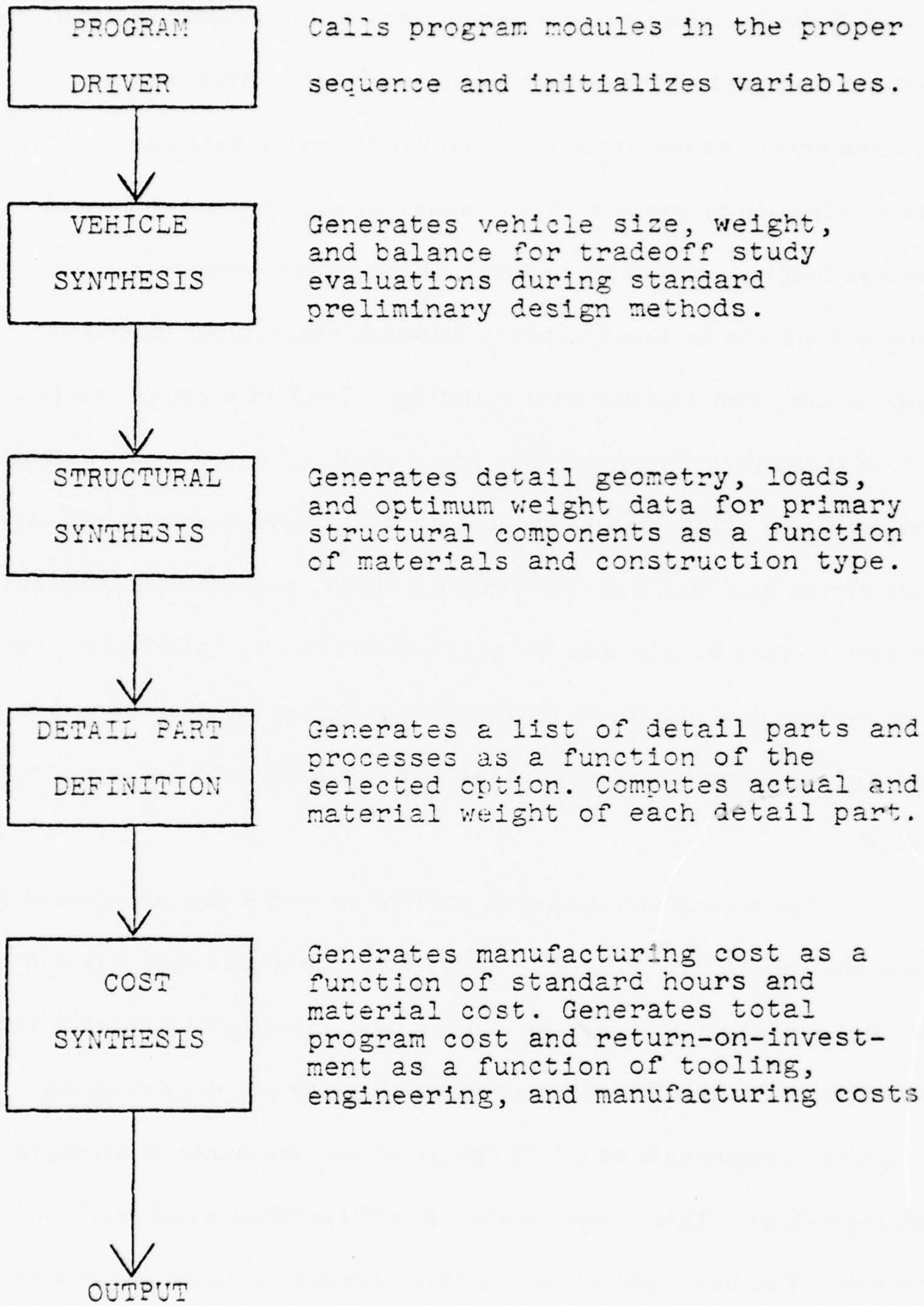


Figure 3. VDEP Program Modules

related directly to key system parameters at the vehicle mission level such as payload, speed, range, and landing field length requirements. At the vehicle configuration level, data can be related directly to surface areas, spar, sweep, taper, etc., and fuselage length, slenderness, etc. At the major component level, comparisons can be made between different materials, modes of construction, and detailed part make-up. Tradeoffs can be made at each of these levels to determine the overall vehicle weight and cost sensitivities. This enables the designer to refine the proposed aircraft design to a high degree of detail. Thus, engineering functions are able to gain insight into the cost effectiveness of alternative aircraft system designs and to determine the impact of more detailed engineering alternatives with respect to any particular aspect of a design.

The structural synthesis module provides detailed geometry loads and weight data for the primary structural elements associated with the aerodynamic surfaces and the basic fuselage structural shell. Structural synthesis provides a means of descriptively designing structural components to fulfill specified requirements of strength and geometry. This program uses a multi-station synthesis process. The basic philosophy of this process is that a set of structural elements can be determined which will satisfy the design criteria at each station and that the aggregation of these elements will

result in a reasonable representation of the structure. It is the structural synthesis portion of the total computer program which contains the subroutine to add or subtract material from the structural elements in an attempt to produce a minimum weight structure. The purpose of this optimization redesign process is to change a given design to produce a lighter weight design while satisfying performance constraints such as minimum gages, positive margins of safety, etc.

The part definition program utilizes the output from the structural synthesis module to derive all the detail parts sufficient to construct the complete assembly of the aircraft. The actual parts weights and the weight of the raw material to be purchased are also derived as part of this module based on the computed part geometry.

The part definition module is coupled with the cost synthesis program through the manufacturing cost analysis. The manufacturing cost analysis consists of a definition of manufacturing processes associated with each part, the standard labor hours, and the material weight. A list of shop operations is called out with each detail part, and a series of equations associated with each operation is used to compute the shop hours (standard hours) necessary to make the part. By applying the appropriate labor rates to the calculated hours, the direct and indirect manufacturing labor costs are found. The material costs are computed based on the amount of material required to

manufacture each part. Additional cost analysis includes tooling, engineering, total program, and return-on-investment costs.

Tooling costs are computed as a function of the number of basic tool manufacturing hours, initial and sustaining hours are derived as a function of the number of dissimilar parts to be produced, the average number of tools required per dissimilar part, and the average number of hours required to produce each tool.

Engineering costs are computed based on the number of manhours necessary to perform the various tasks associated with the development and production of the aircraft. Initial engineering hours are broken down and distributed among the various engineering disciplines based on studies made of historical data.

A learning-curve approach is used to derive costs of a given unit or lot as a function of the first unit cost. Engineering plus the other mentioned costs comprise total program costs. Another area, included for commercial operations, is a return-on-investment cost.

Each of the five modules mentioned above has its own input data requirements. Values that are generated in one module are used as inputs to other modules. This makes possible the generation of data within the program which is difficult or impossible to obtain during aircraft preliminary design. Any time the user desires to set the entire program back to the original data, it can be accomplished

without having to set each parameter to its initial state individually. This allows the user to perform a completely different tradeoff study utilizing initial input data plus new changes.[1]

---

[1] The content of Appendix B is extracted from the user's manual for VDEP-II, Computer Program to Assess Impact of Fatigue and Fracture Criteria on Weight and Cost of Transport Aircraft, General Dynamics, Convair Division, San Diego, CA, September 1974.

APPENDIX C

STATISTICAL ANALYSIS TECHNIQUES

Due to the nature of the data collected, Multiple Linear Regression (MLR) is the appropriate statistical technique to be applied to determine whether there is a relationship between cost and the independent variables: T-bar, weight, structural type, and load factor.

Multiple Linear Regression

The parameters of MLR are represented in the population equation

$$Y = A + B_1X_1 + B_2X_2 + \ldots + B_pX_p$$

where Y is the dependent variable (cost), A is the Y intercept, and B_i are the regression coefficients of the respective independent variables, X_i's (15:328). The population equation is estimated from the equation

$$\hat{y} = a + b_1x_1 + b_2x_2 + \ldots + b_px_p + e,$$

where e refers to the error between the observed value of y and the value of $\hat{y}$ obtained by the regression equation. The objective of regression analysis is to minimize cumulative effects of these errors (8).

The appropriate method for reducing these error effects is the method of least squares (LSM). LSM finds those values of the

regression parameters which minimize the sum of the squared errors, $\sum (e_i^2)$ (8).

Several assumptions are required in MLR analysis. Assumptions pertaining to the error functions are referred to as the "weak three" and the "strong fourth" (8). They are as follows:

1. e_{x_i}, e_{x_j} are statistically independent.

2. Expected value of the error, $(E(e_{x_i})) = 0$ when measured with respect to the population regression line $(A + B_1X_1 + B_2X_2 + \ldots + B_pX_p)$.

3. Variance of the error, $(V(e_{x_i})) = \sigma^2$, (variance of the population). This assumption is referred to as the "homosedasticity assumption" which means 'like variance.'

4. The "strong fourth" says that e_{x_i} is distributed normally with a mean (average) of 0 and a variance of σ^2, e.g. $e_{x_i} \sim N(0, \sigma^2)$. This assumption is necessary in order to make statistical inferences concerning coefficients a and b_i.

The following three assumptions and limitations are also necessary for the use of MLR:

1. The number of sample observations must be greater than the number of population parameters estimated, $n > p$.

2. The sample observations of the independent variables are linearly independent.

3. Independent variables are observed or measured without

error. Error is assumed to exist only when measuring the dependent variable Y (8).

Once these assumptions have been made, the variables are classified and the analysis may proceed.

Variable Classification

The independent variables for this research effort were a combination of two levels of data. The information for rib spacing, load factor, and weight was ratio level data. However, structural types were categorical variables at the nominal data level. For these categorical variables, it was necessary to use the method of differences technique to encode these variables for multiple linear regression (8).

The method of differences designates one of the levels of the nominal variable as the base level. The base level should be the logical choice as the level against which direct relative difference comparisons can be made by examining the variable coefficients. In the absence of a clearly defined advantage in selecting the variable level which is to serve as the base level, a general rule of thumb is to select the level having the fewest occurrences among sample observations (8).

AFFDL Structures Division did not indicate a preference for the structural type to be encoded as the base level variable. Therefore, integral tee was randomly designated as the base level of

structure. With this base level selected, the MLR model data was recorded using a one (1) each time a given categorical variable appeared in an observation and a zero (0) otherwise. For example:

Rib Spacing	Int Blade	Int Zee	Separate Jay	Load Factor
26.	1	0	0	374853.
26.	0	1	0	1874853.
26.	0	0	1	1274853.
26.	0	0	0	3674853.

It should be noted that in the last line of the table above, the designated base level nominal variable manifests itself as zeros in the other nominal variables in the data file. This is a weakness in the method of differences. "It is possible to extract from the regression coefficients the value of the contribution of y resulting from the nominal variable's base level as opposed to having no nominal variable information [8]."

Analysis

The primary means for analyzing the data was the Honeywell 635 computer (CREATE) at Wright-Patterson AFB, Ohio. The data was analyzed using the Statistical Package for the Social Sciences (SPSS), version 6.0. "SPSS is an integral system of computer programs designed for the analysis of social science data [15:1]." SPSS

includes a multiple regression capability in addition to descriptive statistics (15:1).

SPSS has a routine which controls the order of data entry into the regression equation for each of the independent variables (15:451). The forward inclusion scheme is the method used to enter the data. Independent variables enter into the equation in their order of decreasing net or marginal contribution to the explained variation (8). A given variable is eligible for selection only if its partial F ratio is sufficiently large, based on criteria already established within SPSS. Partial F means the likelihood ratio of equality on the test variable over all groups, given the distribution produced by the variables already entered. This F ratio is called the F-to-enter ratio (15:453). The forward inclusion scheme thus insures that the most significant variables enter the regression equation first.

In addition to the regression equation, SPSS output includes the values of three types of variation: explained, unexplained, and total. Explained variation (EV) refers to the component of variation due to or accounted for by the regression $(\hat{y}-\overline{y})^2$ (8). EV is also termed the sum of squares regression (SSR) (15:383; 3:465). Unexplained variation (UV) refers to the component of variation due to, unaccounted for, or unexplained by regression. It is the component of variation about regression (8). UV is also known as the sum of squares residual or sum of squares error (SSE) (15:383; 3:465).

Total variation (TV) is the sum of EV and UV. Another title for TV is the sum of squares total (SST) (15:383; 3:465). Thus, SST = SSR + SSE. This concept is important to help understand the relationship that exists between the dependent variable and the independent variables.

Another output from SPSS MLR is the coefficient of determination (R^2) (15:364). R^2 is a measure of the extent to which a linear multiple regression equation fits the observed data (3:620). A maximum likelihood estimator of the universe coefficient of determination can be found by dividing SSR by SST (3:620). An explanation of the test for significance of R^2 is found under the section Hypothesis Testing.

The regression coefficients (B_i's) are the third major section of the SPSS output. The B_i is important because it represents the expected change in Y with a change in one unit of X_i when all other X_i's are held constant or otherwise controlled (15:330). This makes the regression coefficients extremely important since they determine the key cost drivers among all the independent variables. As with R^2, B_i's have statistical hypothesis tests for determining the significance of each coefficient.

Hypothesis Testing

The first test on R^2 involves the overall regression equation. The objective is to test the statistical significance of the gross

contribution of all the linear regressors simultaneously. This test indicates whether or not the sample data evidence a linear relationship between Y (cost) and $X_1, X_2, \ldots, X_p$ (8). The appropriate hypothesis test involving R^2 is

$$H_o: R^2 = 0$$

$$H_1: R^2 \neq 0.$$

When H_o is true, $Y = B_o + e$. Hence one may as well use $\overline{Y}$ to estimate Y. When H_1 is true, Y = (at least one B_iX_i) + e (8). The appropriate test statistic is found by the formula $F_o = \frac{SSR}{(p-1)} \div \frac{SSE}{(n-p)}$ where p = the number of parameters in the regression equation and n = the number of sample observations. The test statistic (F_o) follows an F distribution with p-1 upper and n-p lower degrees of freedom under H_o (7). The F test is conducted as a one-sided test. The smaller critical α becomes, the more significant the hypothesis test. The more significant the test, the smaller the probability of rejecting a true hypothesis. If F_o is greater than critical F (F_c), H_o is rejected and the overall linear regression model is adjudged significant. This means at least one regression coefficient is significant (8).

When it is determined that at least one coefficient is significant, it is necessary to statistically test the individual B_i's to determine individual significance. The hypothesis test on the net or marginal contribution of X_i is

$$H_o: B_i = 0$$

$$H_1: B_i \neq 0.$$

The test statistic is

$$F_o = \frac{\text{SSR (due to X) x (n-p)}}{\text{SSE}} \quad (8).$$

The test on statistical significance of B_i may be conducted in one of two ways, (1) in isolation, or (2) with K other independent variables. The conservative approach is taken by testing the B_i values simultaneously. This necessitates the use of an equivalent-α level with which to conduct the test. Bonferroni's approach computes an equivalent $\alpha = \alpha \div K+1$ (where K = other independent variables). With an α-level of 0.10, the equivalent α is dependent upon the number of independent variables included in the regression equation (8). If $F_o > F_c$ with one upper and n-p lower degrees of freedom at an equivalent α-level, the respective H_o is rejected and the conclusion reached that the applicable B_i is significant to the regression equation.

There are three possible interpretations for a lack of statistical significance of one or more X_i's:

1. The sample size is too small to give insight into the true relationship among variables.

2. Multicollinearity is present. A solution is to use a well-designed experiment where complete control is exercised over all independent variables.

3. X_i does not contribute to the regression equation. A solution is to look to a model without X_i. If acceptable, throw away X_i (8).

Partial Correlation Analysis

The basic formula for the computation of partial coefficients is

$$r_{ij.k} = \frac{r_{ij} - (r_{ik})(r_{jk})}{\sqrt{1-r_{ik}^2}\sqrt{1-r_{jk}^2}}$$

where k is the control variable and i and j are the independent and dependent variables. r is the partial correlation coefficient.

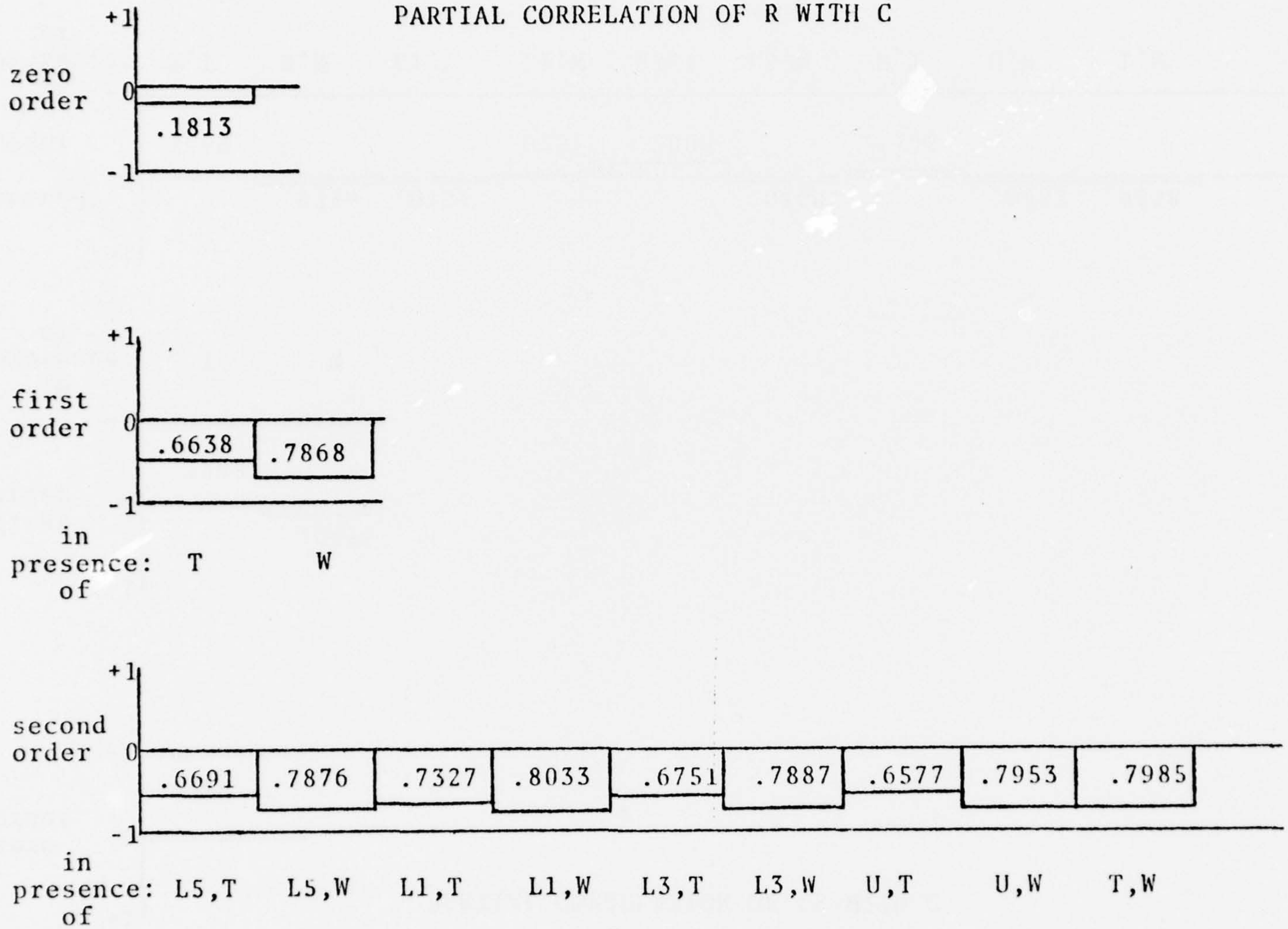
The extension of this formula to more than one control variable (that is, n+1) is made by replacing the simple correlation coefficients (or zero-order partials) on the right side of the equation with the n^{th}-order partial coefficients. In this way the preceding formula can be used to recursively define and compute each higher-order partial from the previous one (15:302-3).

Partial correlation analysis is thus used as a tool to aid in understanding and clarifying relationships between cost, weight, T-bar, rib spacing, load, integral blade, integral zee, and separate jay.

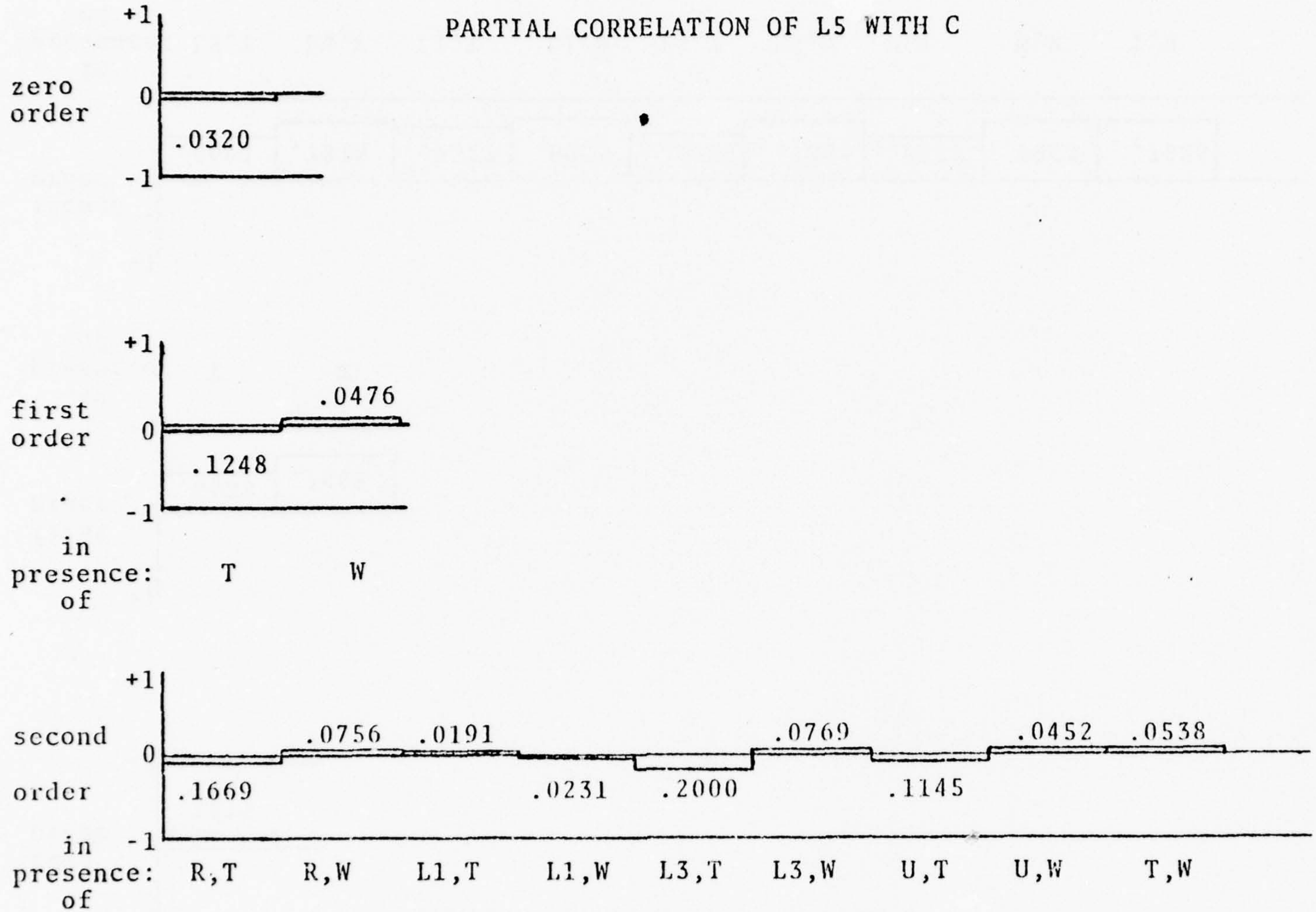
APPENDIX D

PARTIAL CORRELATION COEFFICIENTS

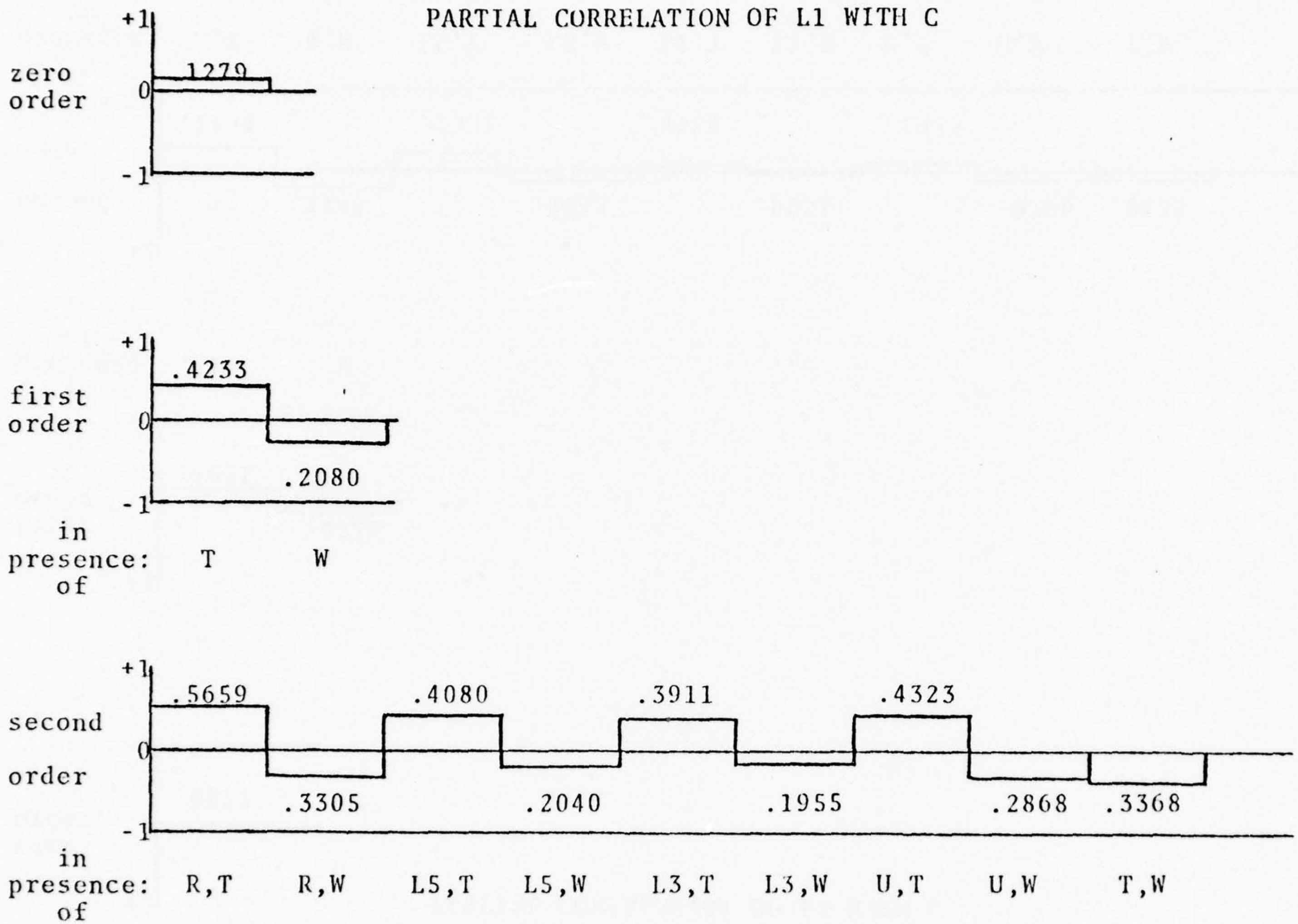
PARTIAL CORRELATION OF R WITH C



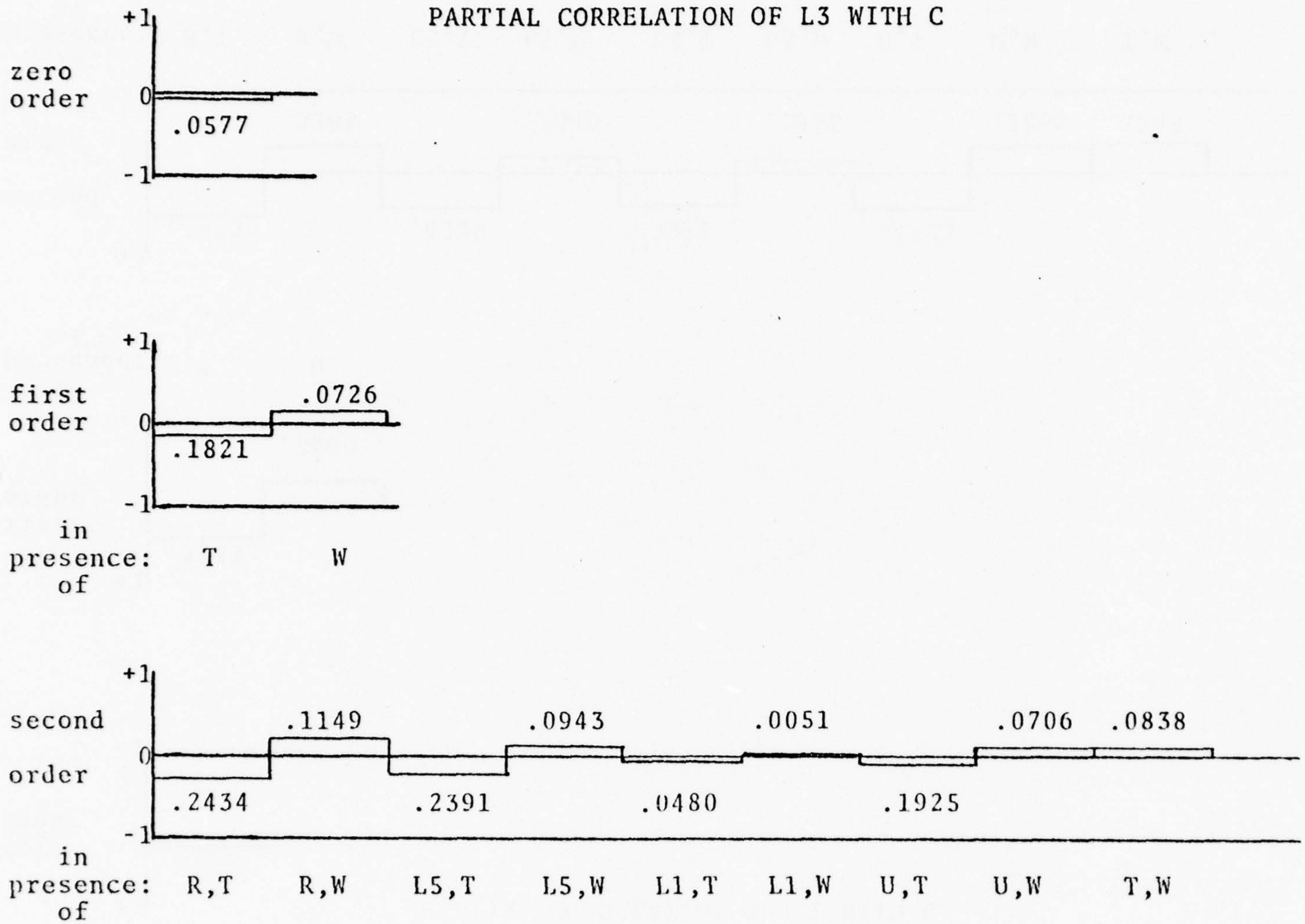
PARTIAL CORRELATION OF L5 WITH C

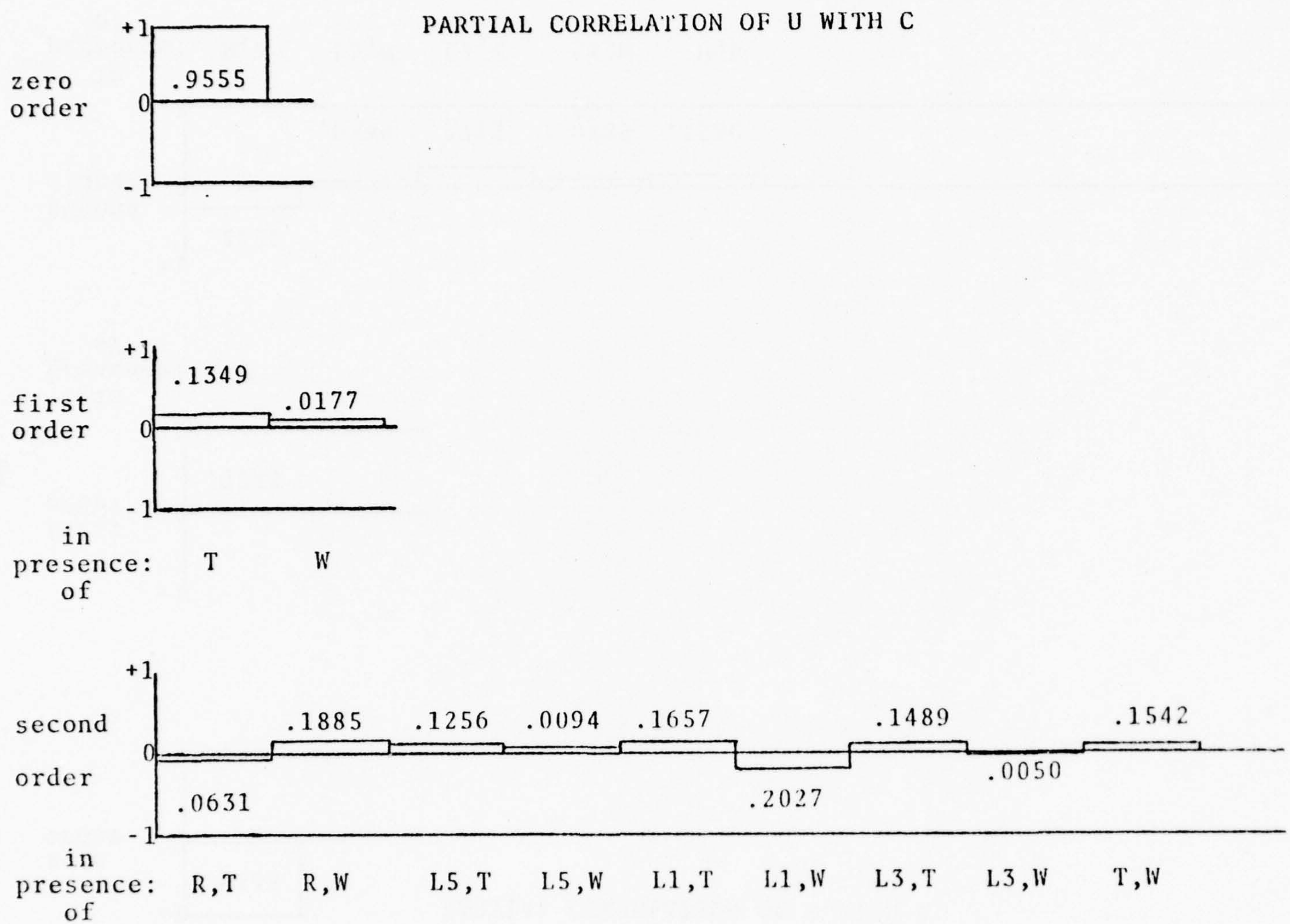


PARTIAL CORRELATION OF L1 WITH C

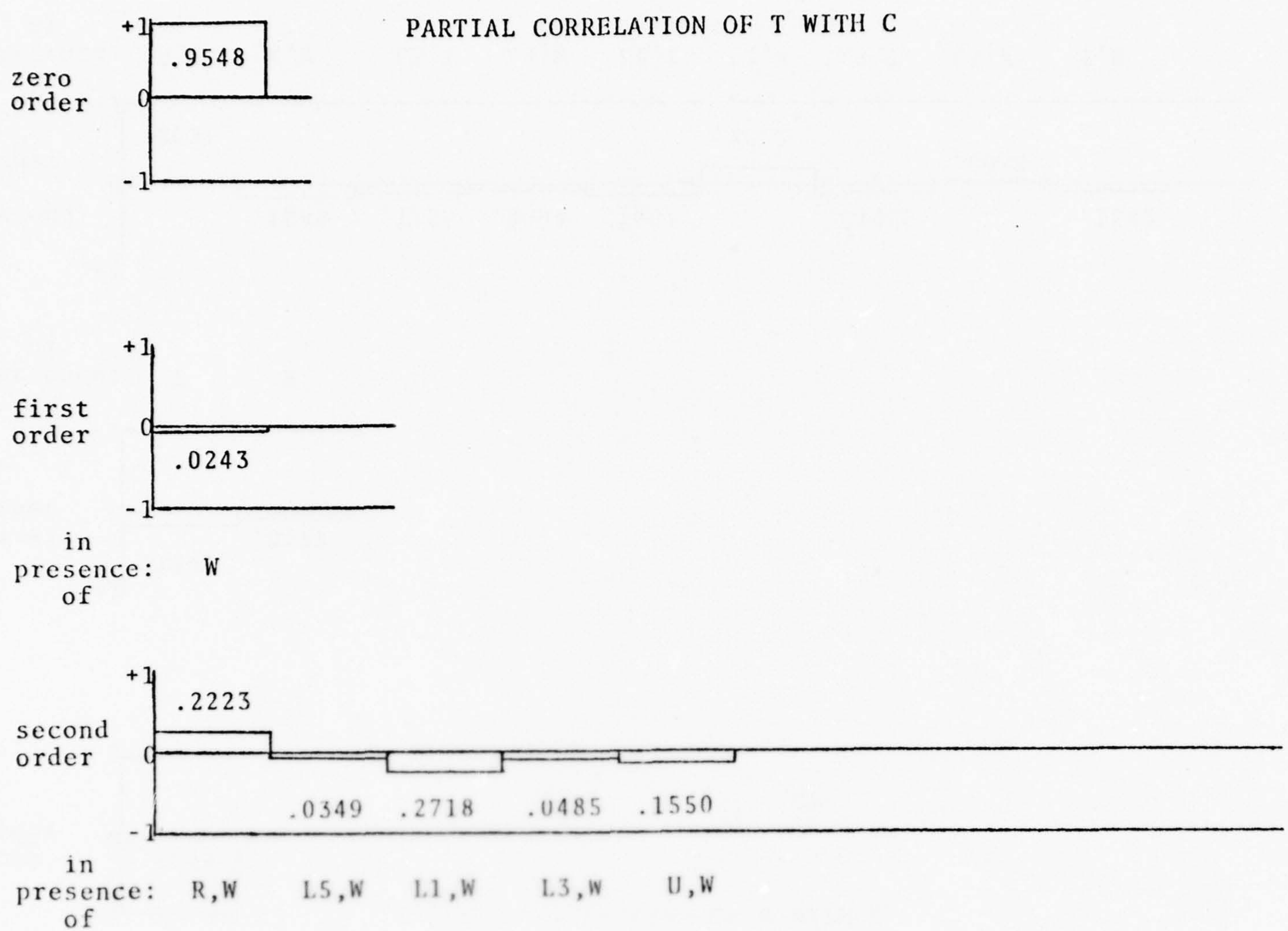


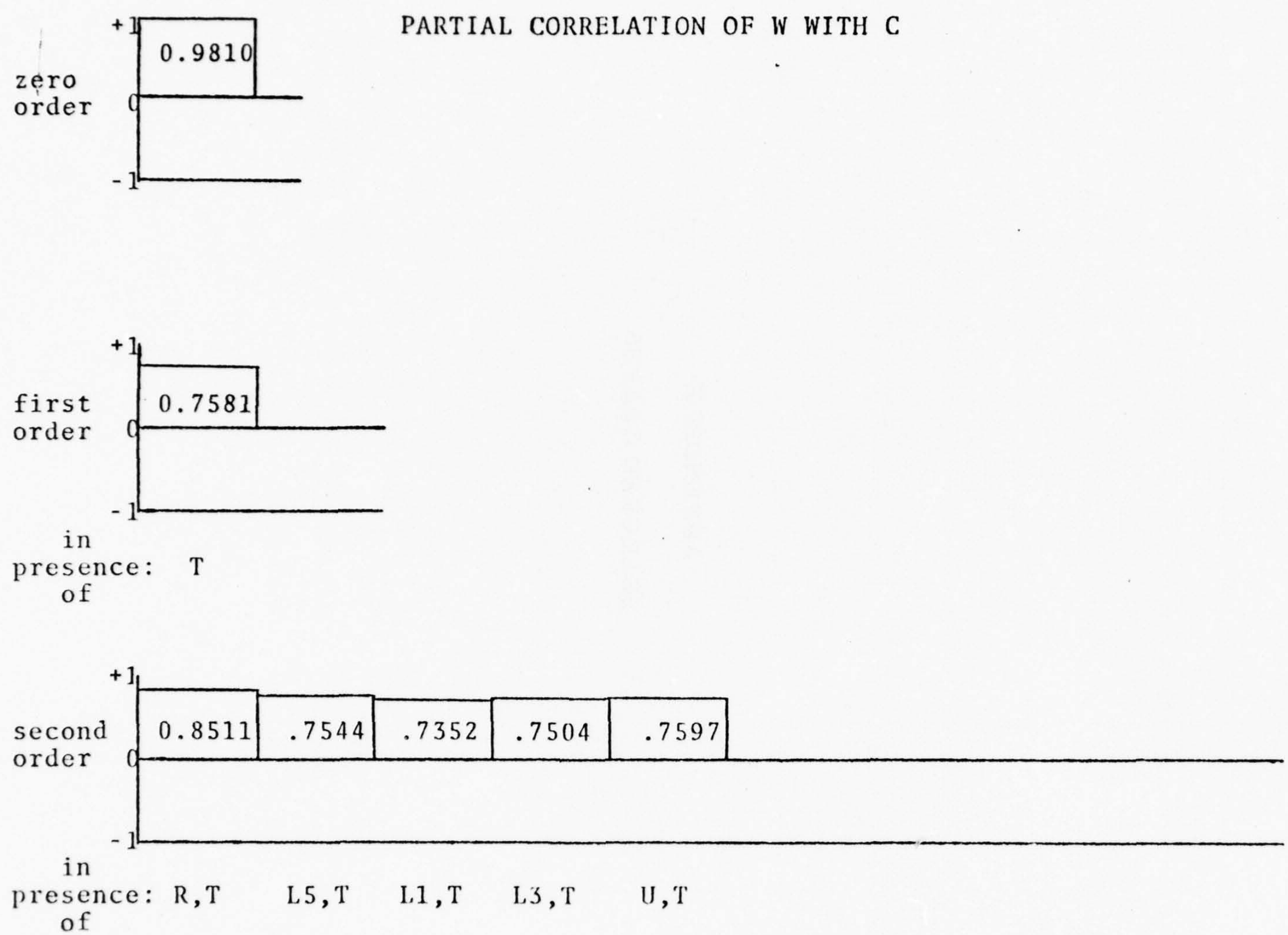
PARTIAL CORRELATION OF L3 WITH C




PARTIAL CORRELATION OF U WITH C
zero order
+1
0
-1
.9555
first order
.1349
.0177
in presence of: T W
second order
.0631
.1885
.1256
.0094
.1657
.2027
.1489
.0050
.1542
in presence of: R,T R,W L5,T L5,W L1,T L1,W L3,T L3,W T,W

PARTIAL CORRELATION OF T WITH C




PARTIAL CORRELATION OF W WITH C
zero order
+1
0
-1
0.9810
first order
+1
0
-1
0.7581
in presence of: T
second order
+1
0
-1
0.8511
.7544
.7352
.7504
.7597
in presence of: R,T L5,T L1,T L3,T U,T

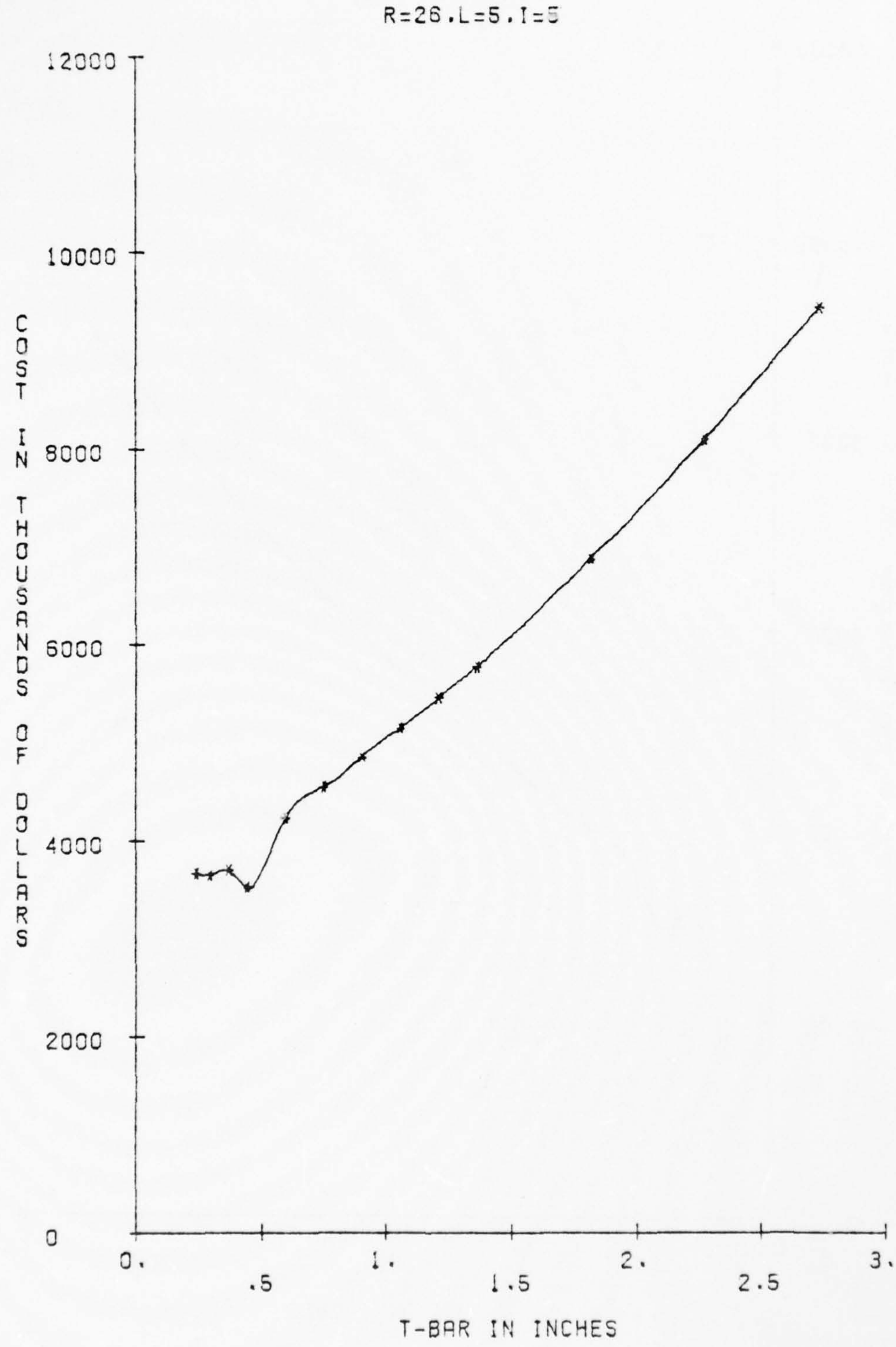
APPENDIX E

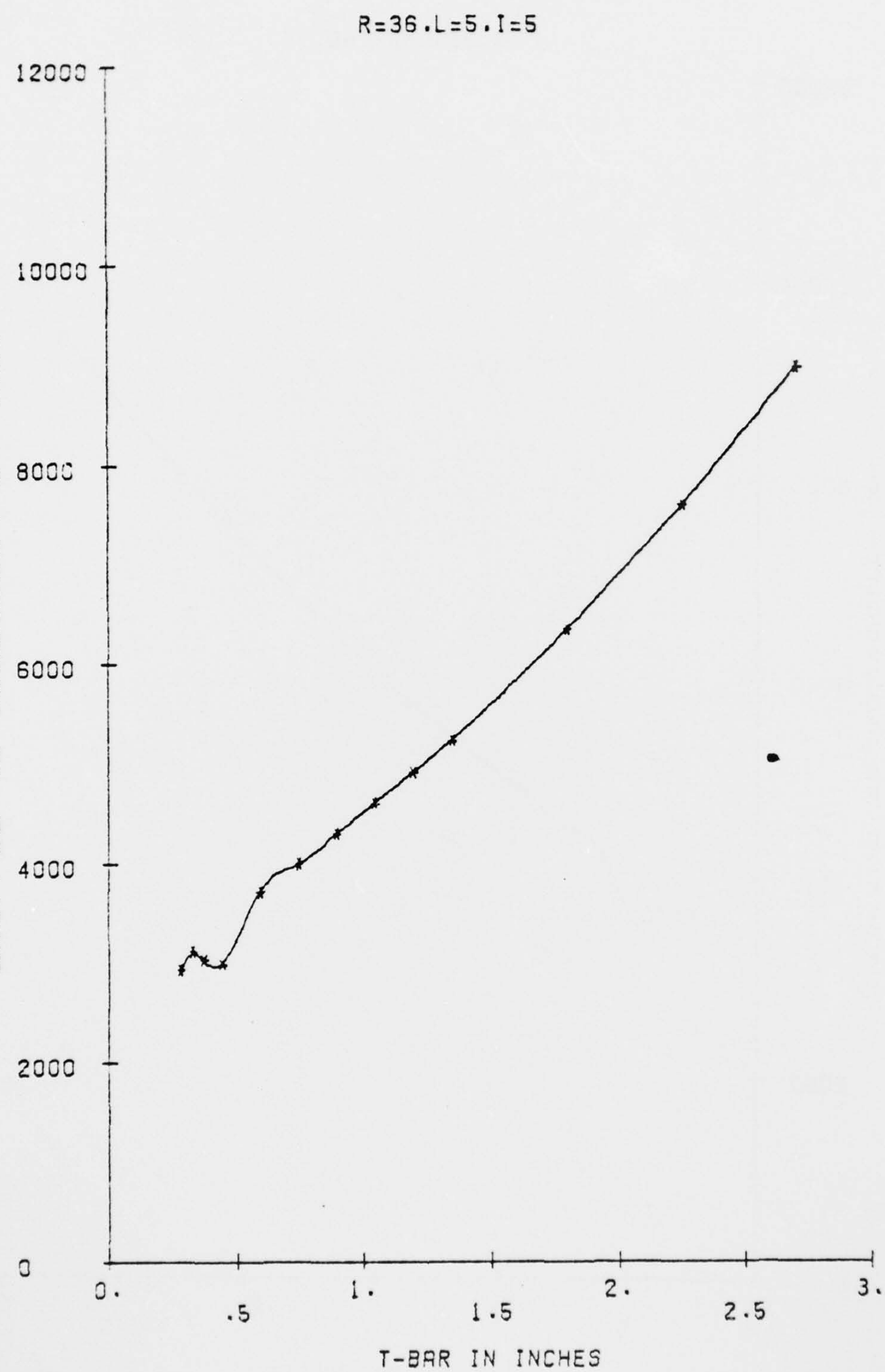
SELECTED GRAPHS

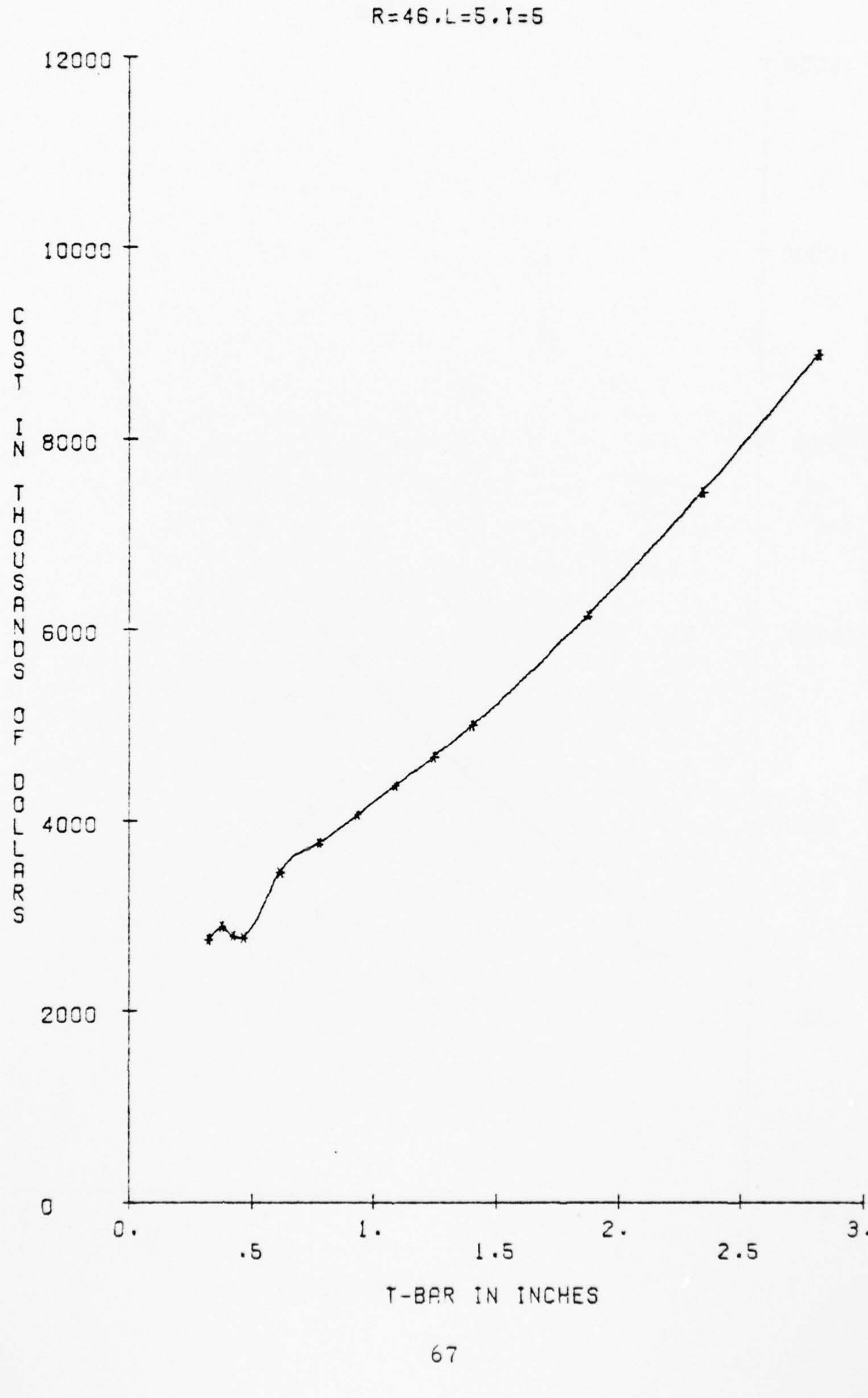
This appendix is broken into two sections. The first contains the twenty-four graphs that resulted when T-bar was plotted against cost for a given rib spacing (R) and structural type (Li) over the range of load (U). The second section contains ten selected plots of weight versus cost following the same criteria as for T-bar.

SECTION I

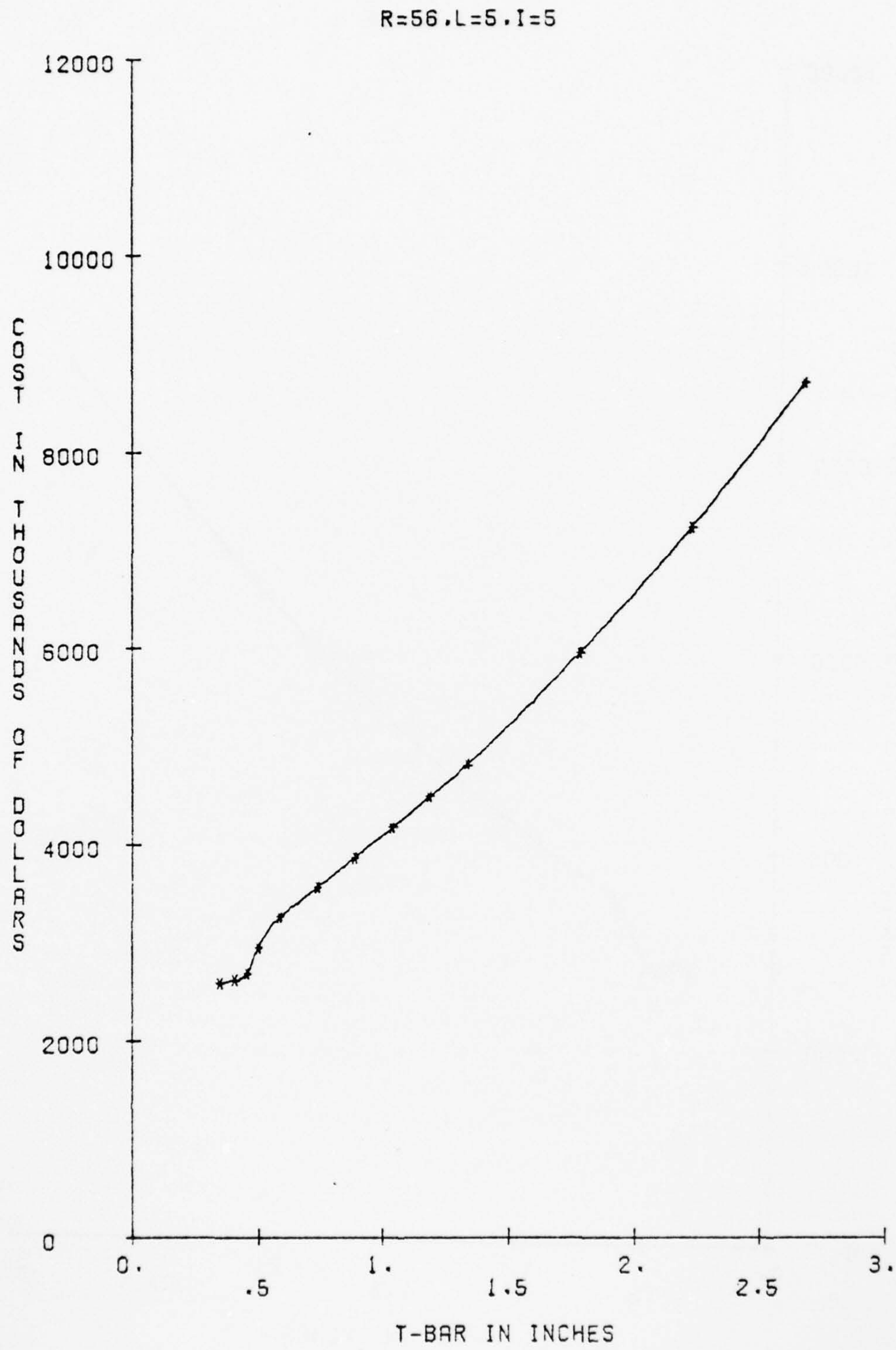
COST VS T-BAR

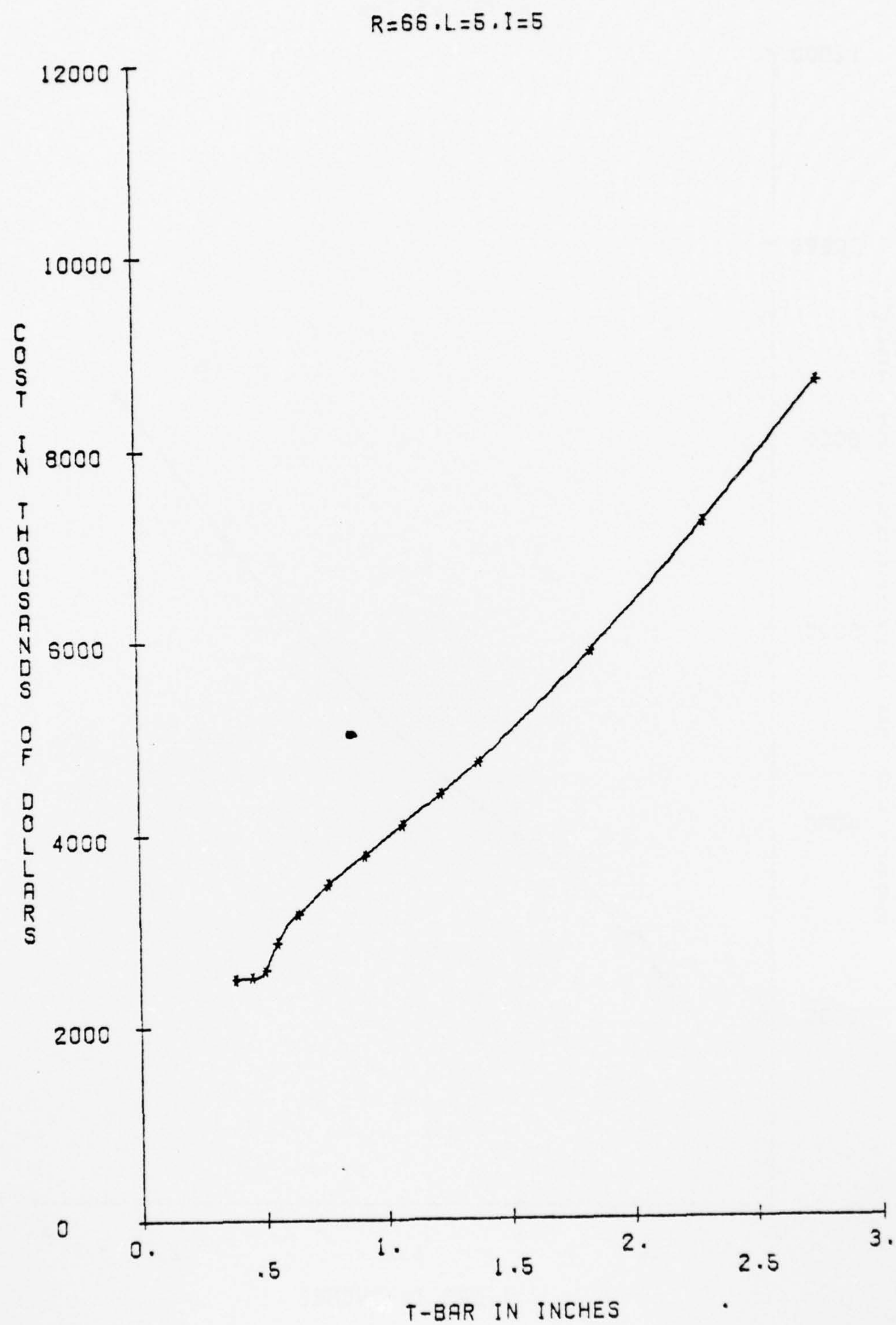

R=26.L=5.I=5
12000
10000
8000
6000
4000
2000
0
COST IN THOUSANDS OF DOLLARS
0.
.5
1.
1.5
2.
2.5
3.
T-BAR IN INCHES

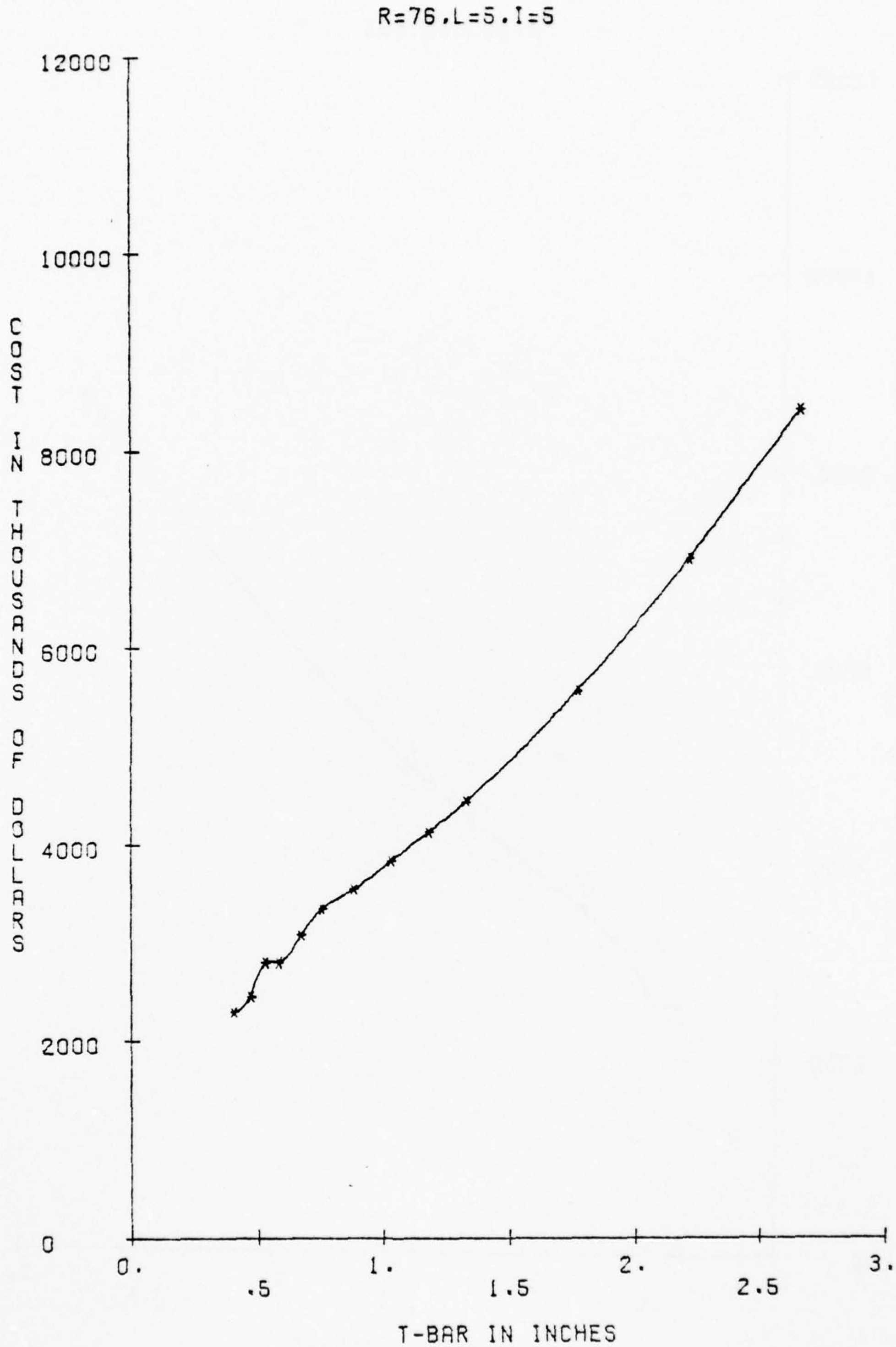

R=36.L=5.I=5
12000
10000
8000
6000
4000
2000
0
COST IN THOUSANDS OF DOLLARS
0.
.5
1.
1.5
2.
2.5
3.
T-BAR IN INCHES

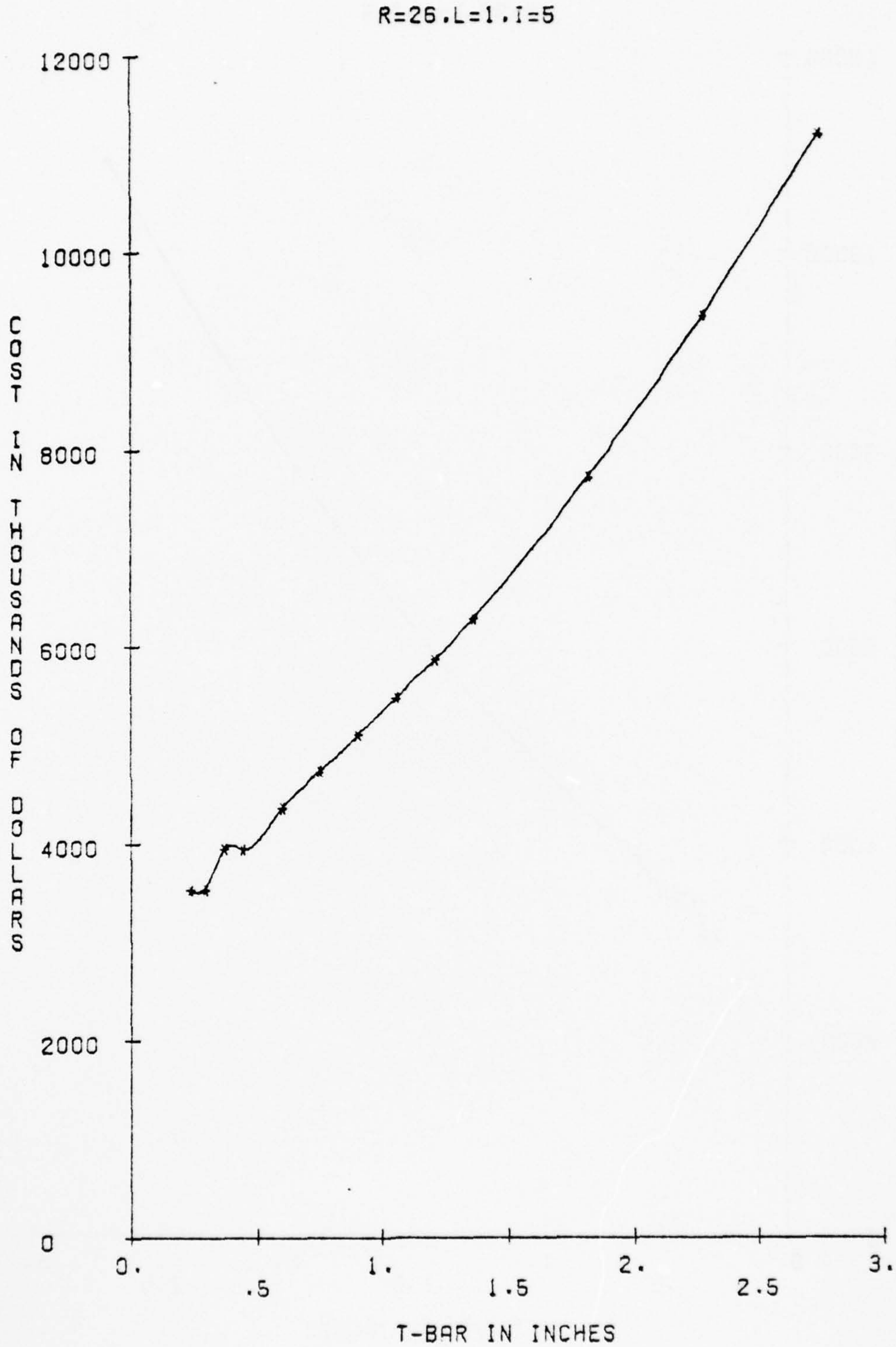


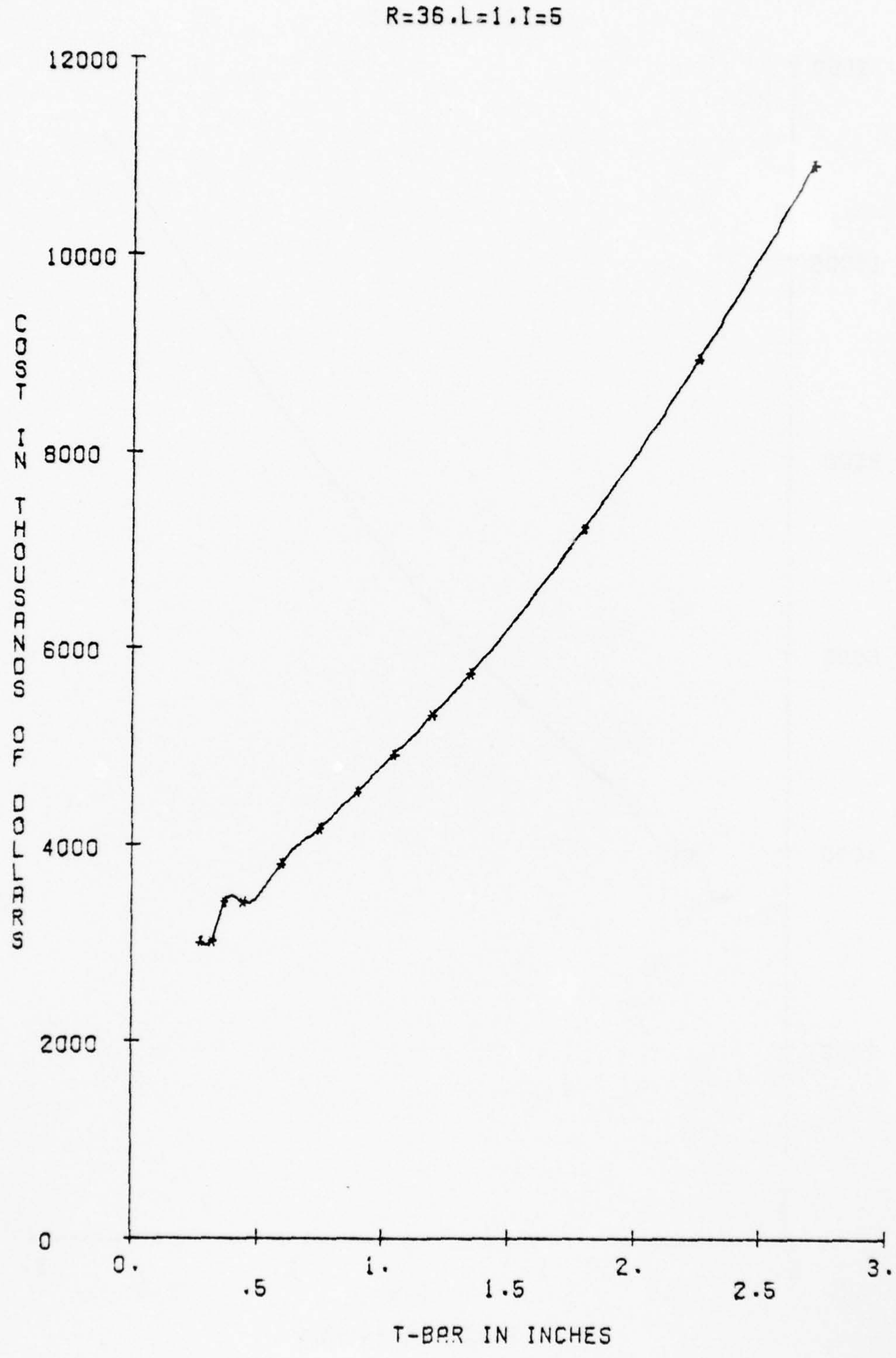
R=46.L=5.I=5
12000
10000
8000
6000
4000
2000
0
COST IN THOUSANDS OF DOLLARS
0.
.5
1.
1.5
2.
2.5
3.
T-BAR IN INCHES

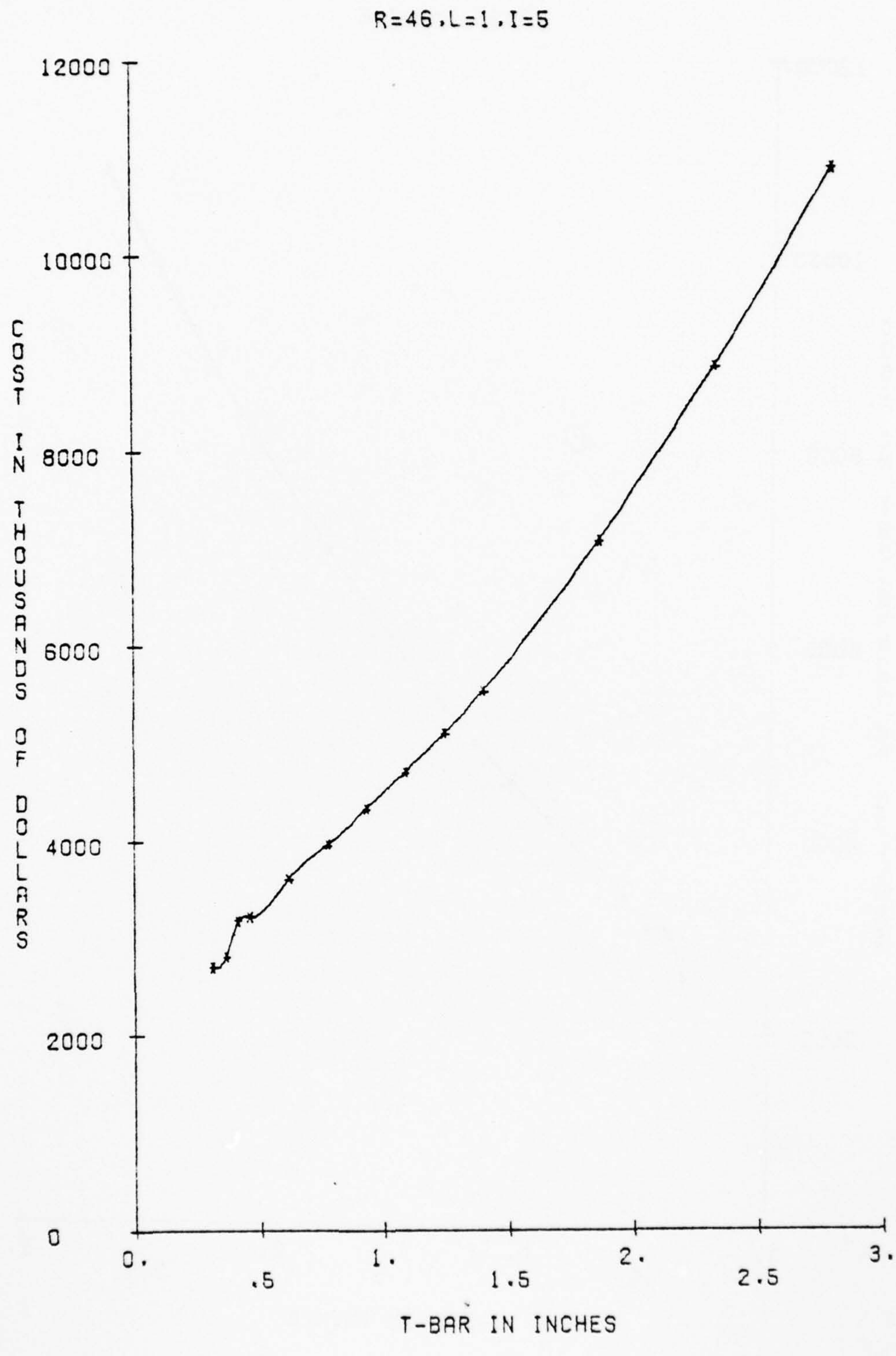

R=56.L=5.I=5
12000
10000
8000
6000
4000
2000
0
COST IN THOUSANDS OF DOLLARS
0.
.5
1.
1.5
2.
2.5
3.
T-BAR IN INCHES

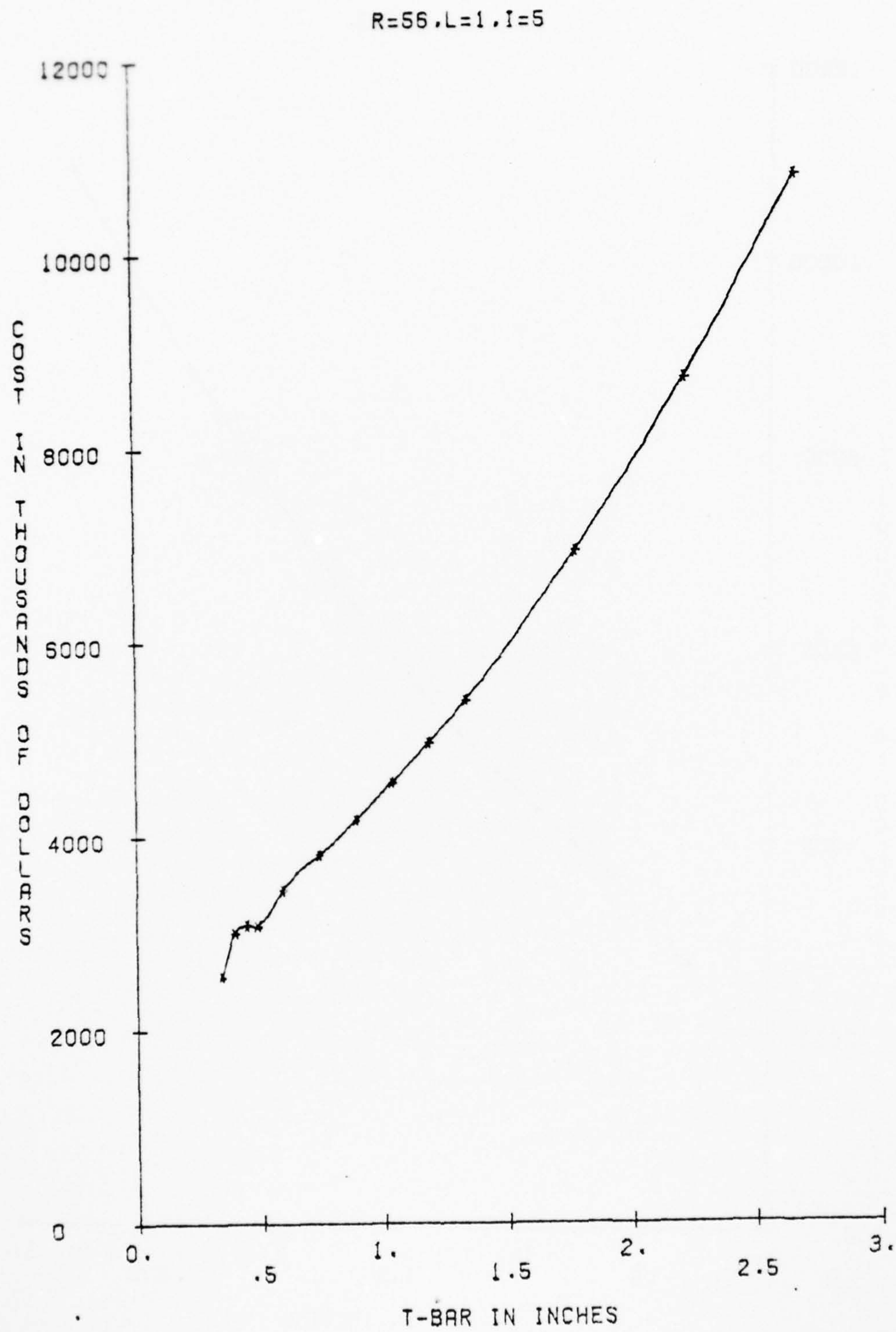

R=66.L=5.I=5
12000
10000
8000
6000
4000
2000
0
COST IN THOUSANDS OF DOLLARS
0.
.5
1.
1.5
2.
2.5
3.
T-BAR IN INCHES

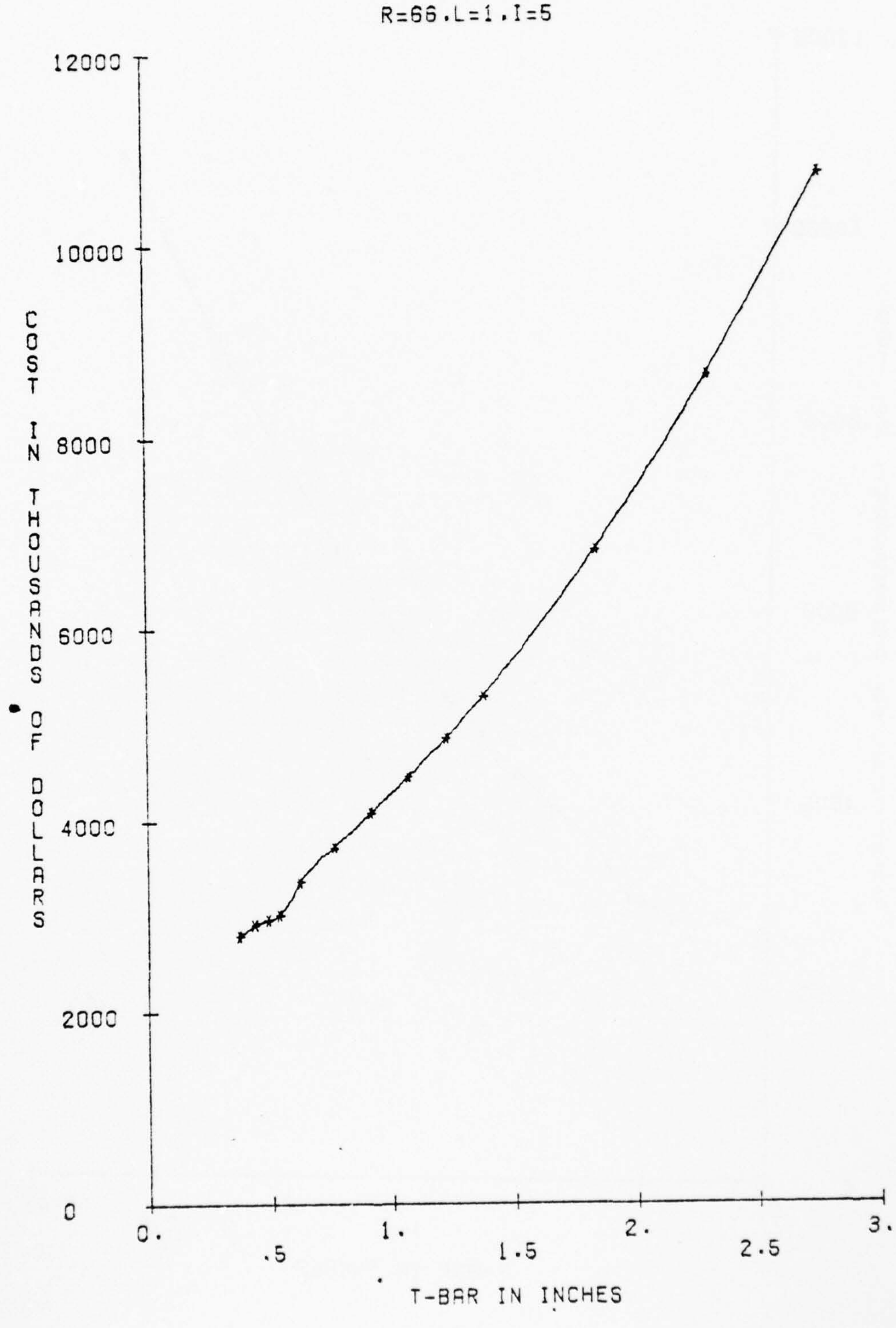

R=76.L=5.I=5
COST IN THOUSANDS OF DOLLARS
12000
10000
8000
6000
4000
2000
0
0.
.5
1.
1.5
2.
2.5
3.
T-BAR IN INCHES

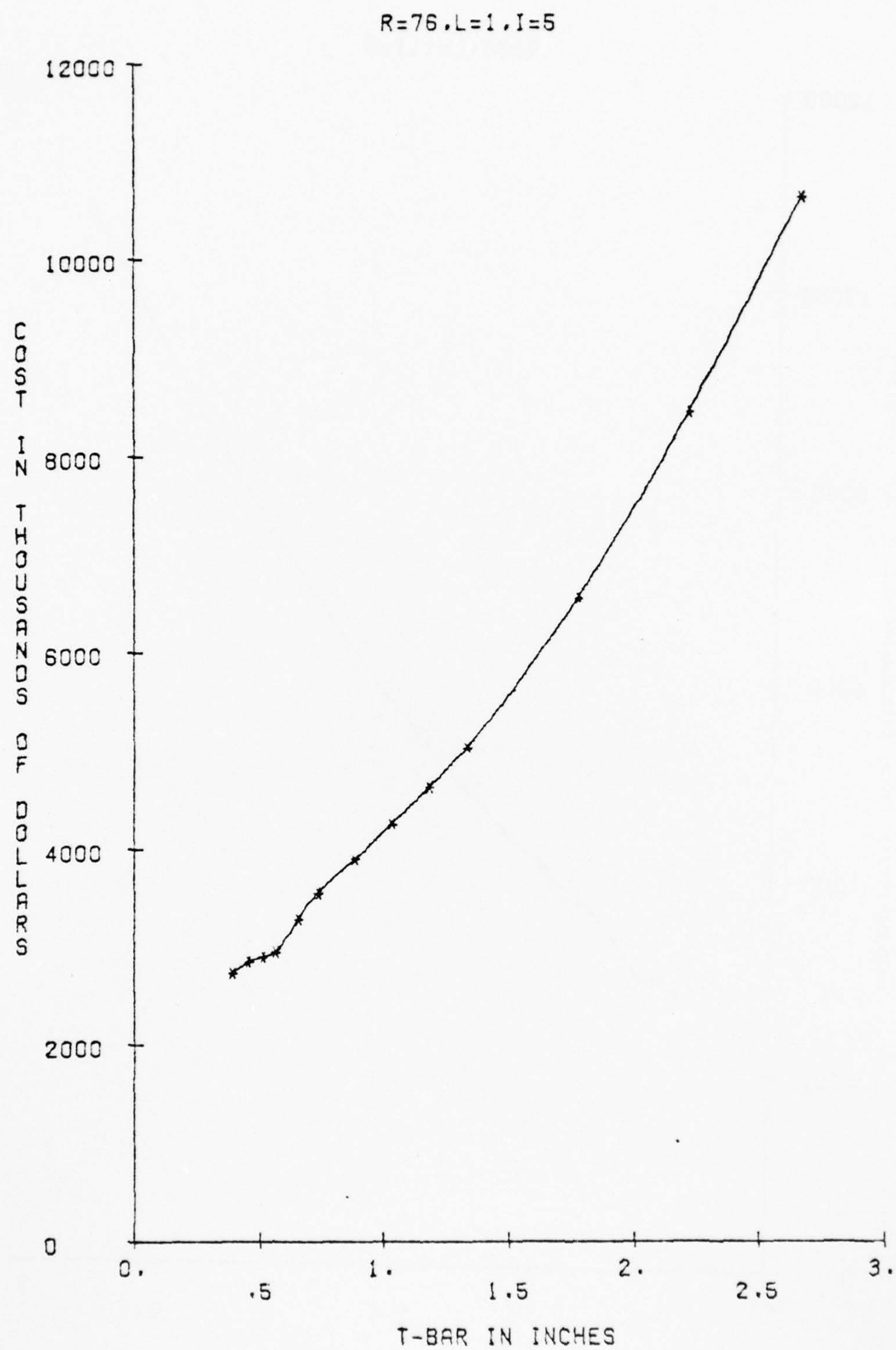

R=26.L=1.I=5
COST IN THOUSANDS OF DOLLARS
12000
10000
8000
6000
4000
2000
0
0.
.5
1.
1.5
2.
2.5
3.
T-BAR IN INCHES

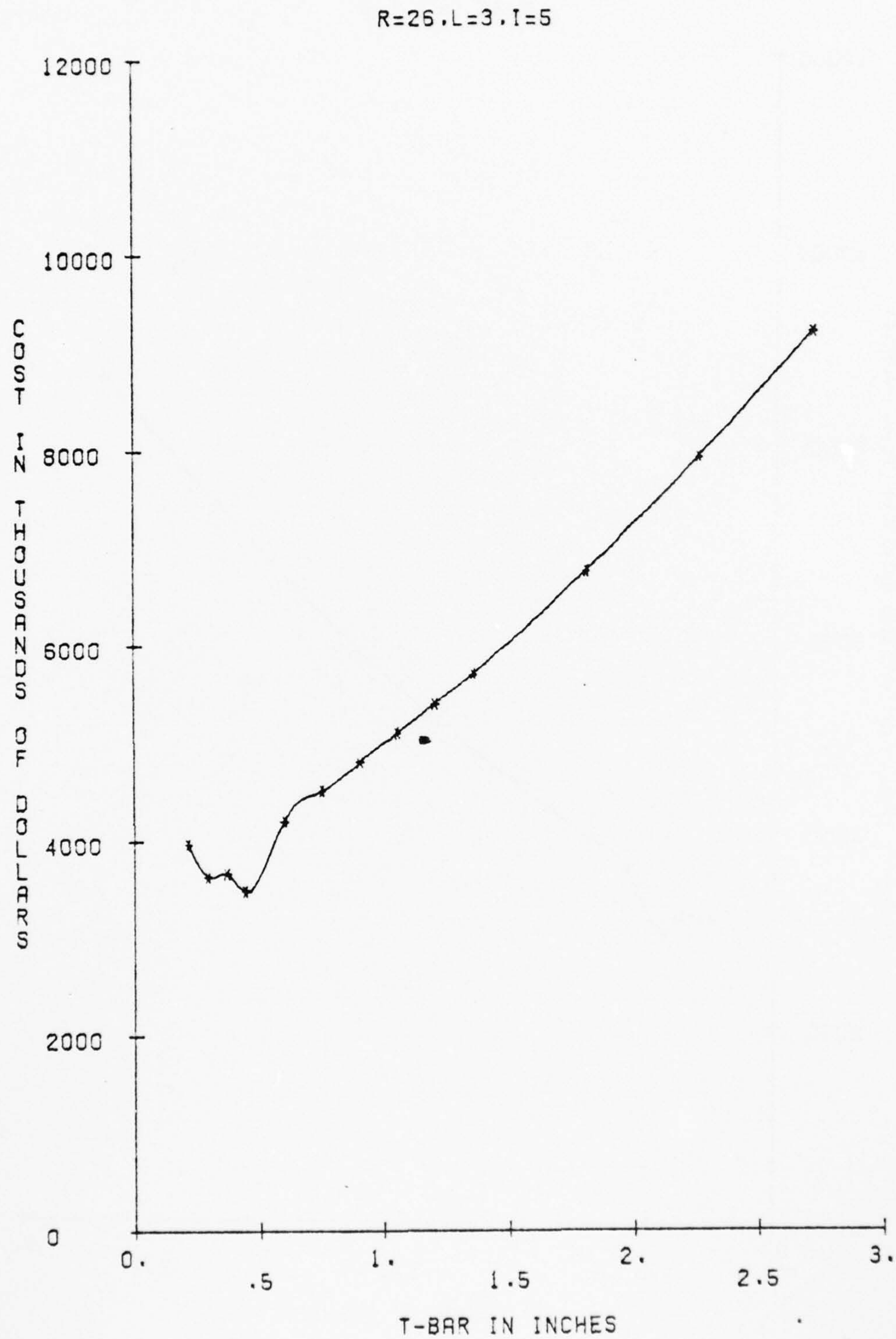

R=36.L=1.I=5
12000
10000
8000
6000
4000
2000
0
COST IN THOUSANDS OF DOLLARS
0.
.5
1.
1.5
2.
2.5
3.
T-BAR IN INCHES

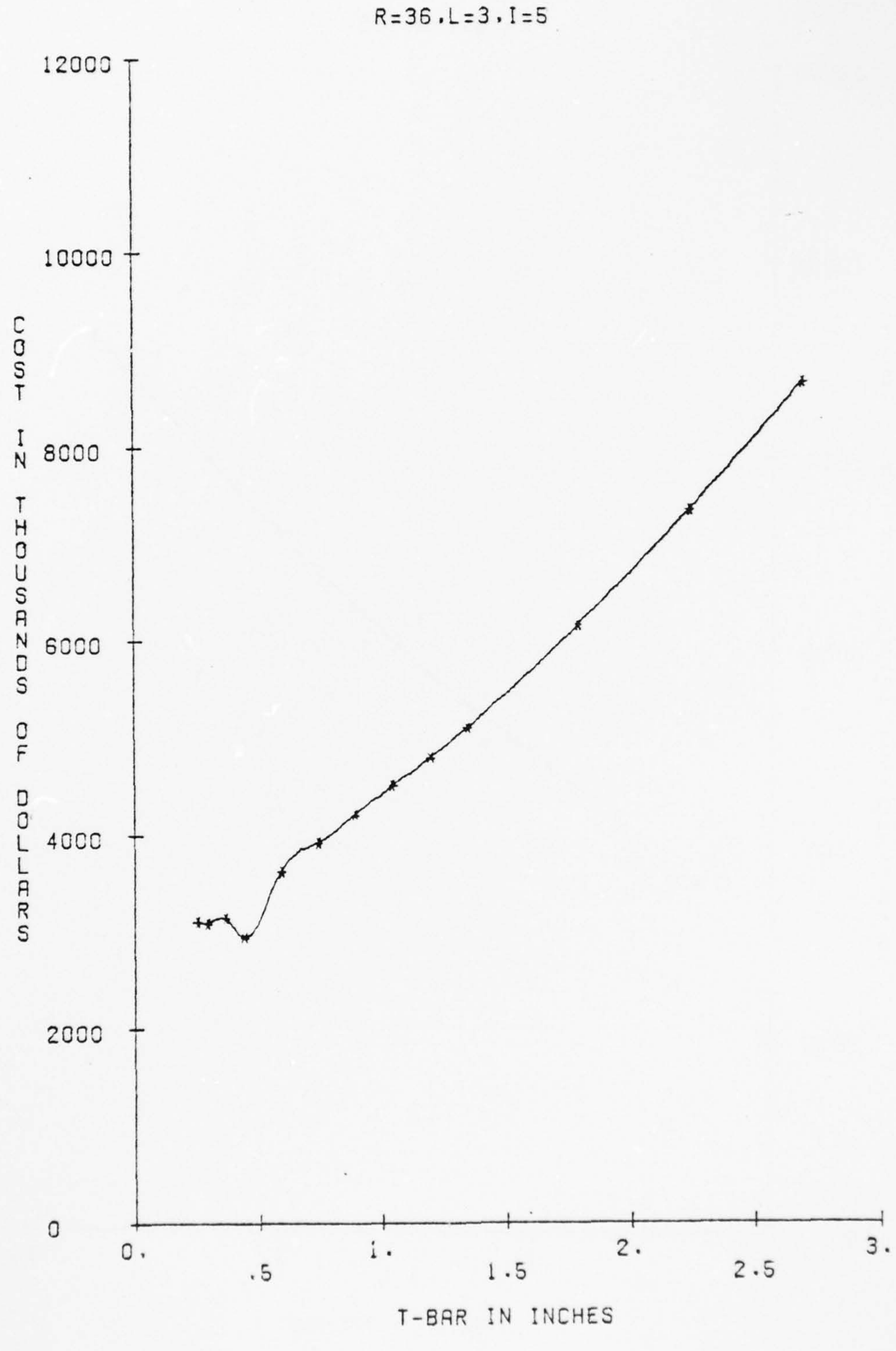

R=46,L=1,I=5
COST IN THOUSANDS OF DOLLARS
12000
10000
8000
6000
4000
2000
0
0.
.5
1.
1.5
2.
2.5
3.
T-BAR IN INCHES


R=56.L=1.I=5
12000
10000
8000
6000
4000
2000
0
COST IN THOUSANDS OF DOLLARS
0.
.5
1.
1.5
2.
2.5
3.
T-BAR IN INCHES


R=66.L=1.I=5
COST IN THOUSANDS OF DOLLARS
12000
10000
8000
6000
4000
2000
0
0.
.5
1.
1.5
2.
2.5
3.
T-BAR IN INCHES


R=76,L=1,I=5
12000
10000
8000
6000
4000
2000
0
COST IN THOUSANDS OF DOLLARS
0.
.5
1.
1.5
2.
2.5
3.
T-BAR IN INCHES


R=26.L=3.I=5
12000
10000
8000
6000
4000
2000
0
COST IN THOUSANDS OF DOLLARS
0.
.5
1.
1.5
2.
2.5
3.
T-BAR IN INCHES

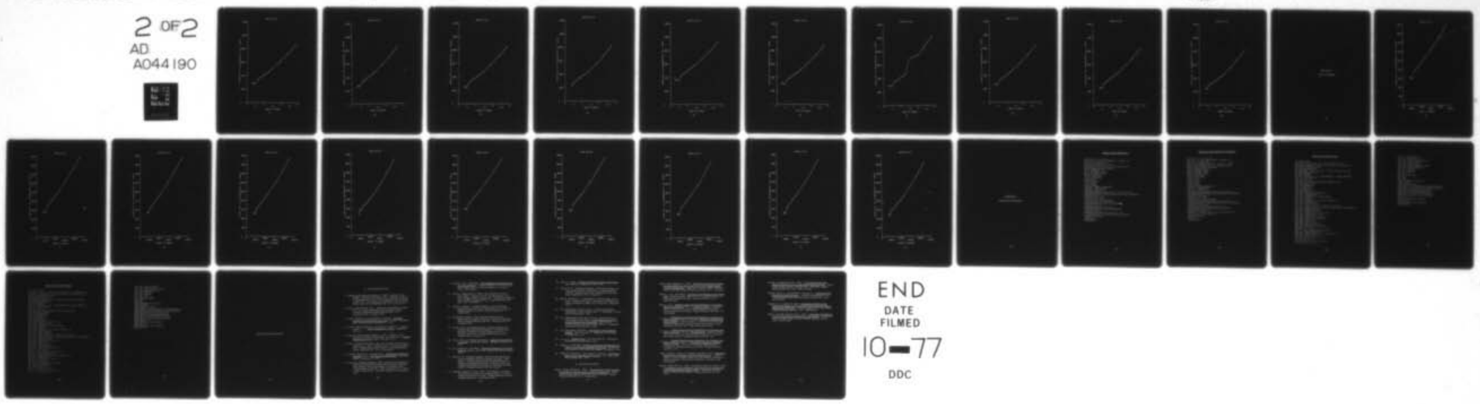


R=36.L=3.I=5
12000
10000
8000
6000
4000
2000
0
COST IN THOUSANDS OF DOLLARS
0.
.5
1.
1.5
2.
2.5
3.
T-BAR IN INCHES

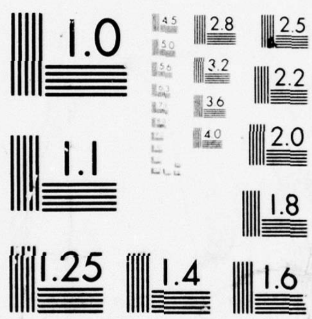
AD-A044 190 AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OHIO SCHO--ETC F/G 1/3
A FEASIBILITY STUDY TO DEVELOP OPTIMIZATION ALGORITHMS FOR AIRC--ETC(U)
JUN 77 R L EVANS, B P CHRISTENSEN

UNCLASSIFIED AFIT-LSSR-30-77A NL

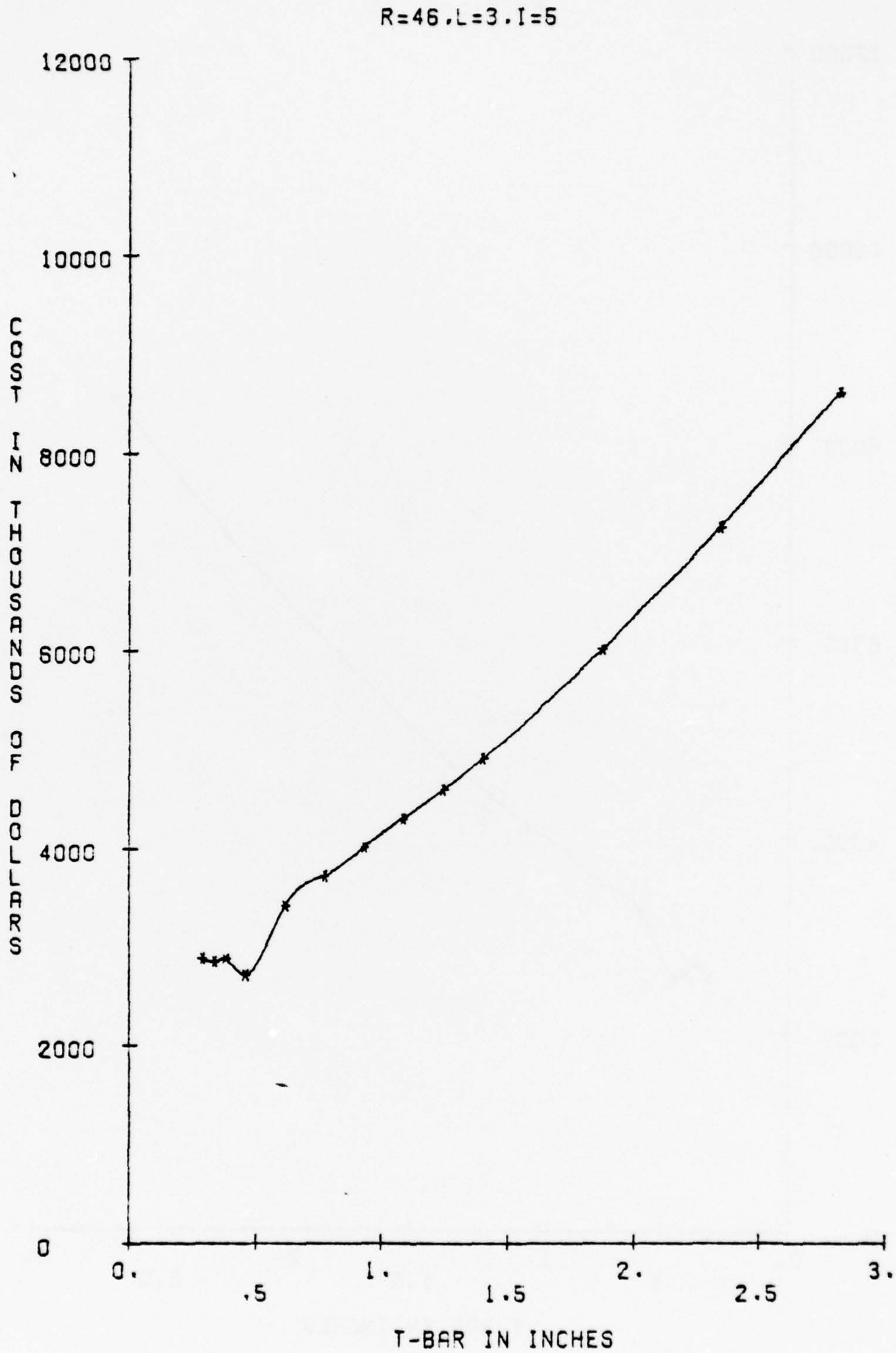
2 OF 2
AD
A044190

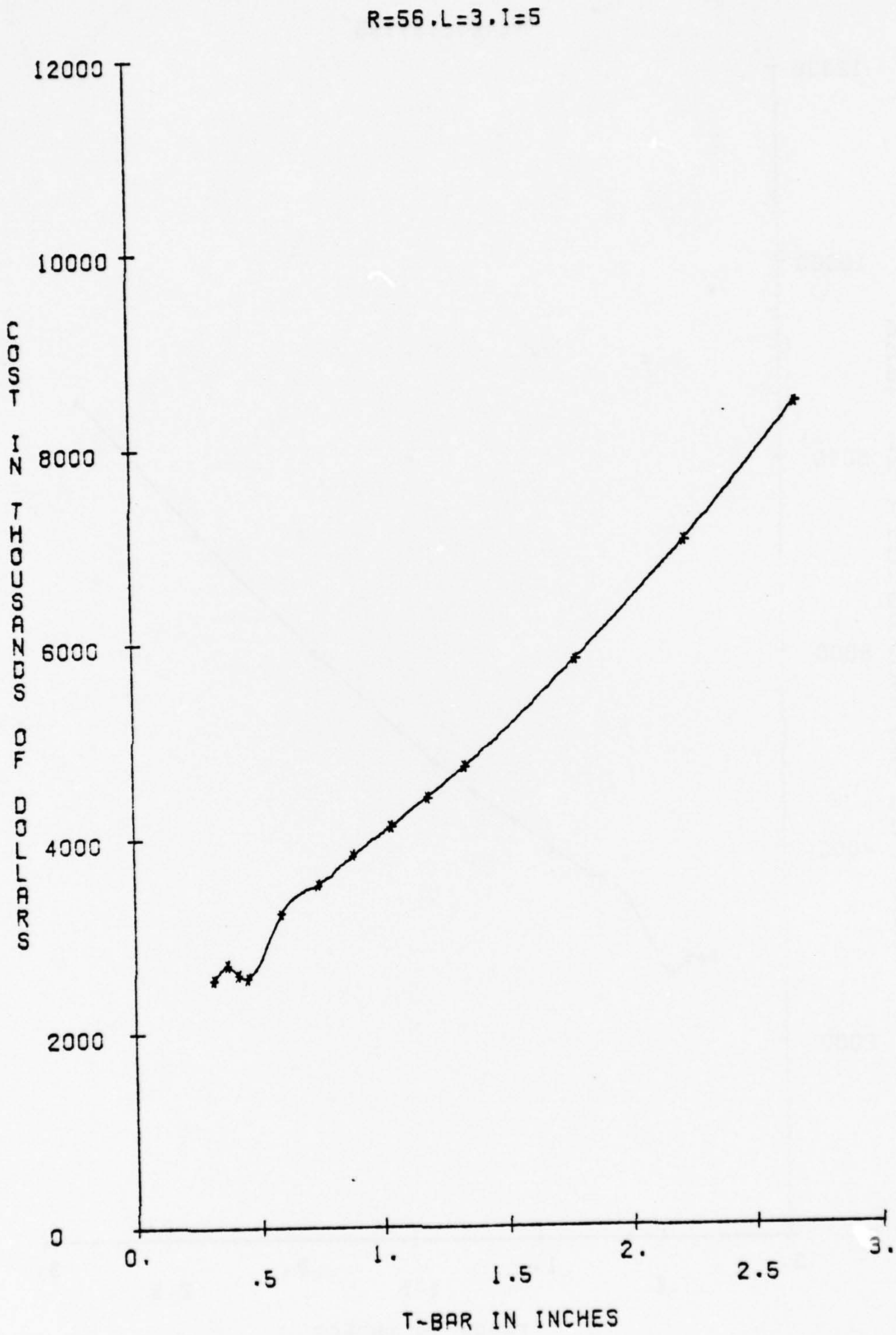


END
DATE
FILMED
10-77
DDC



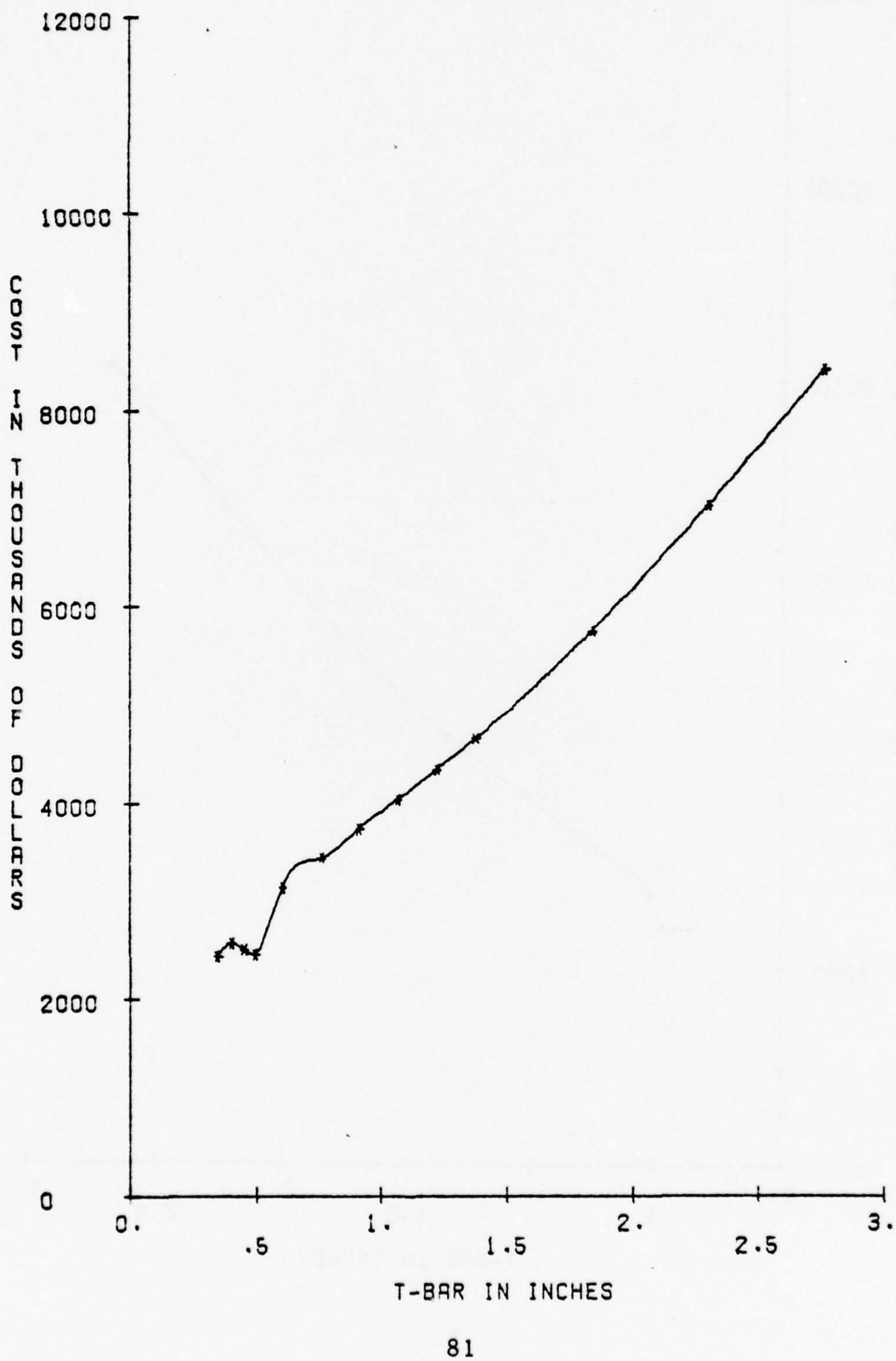
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

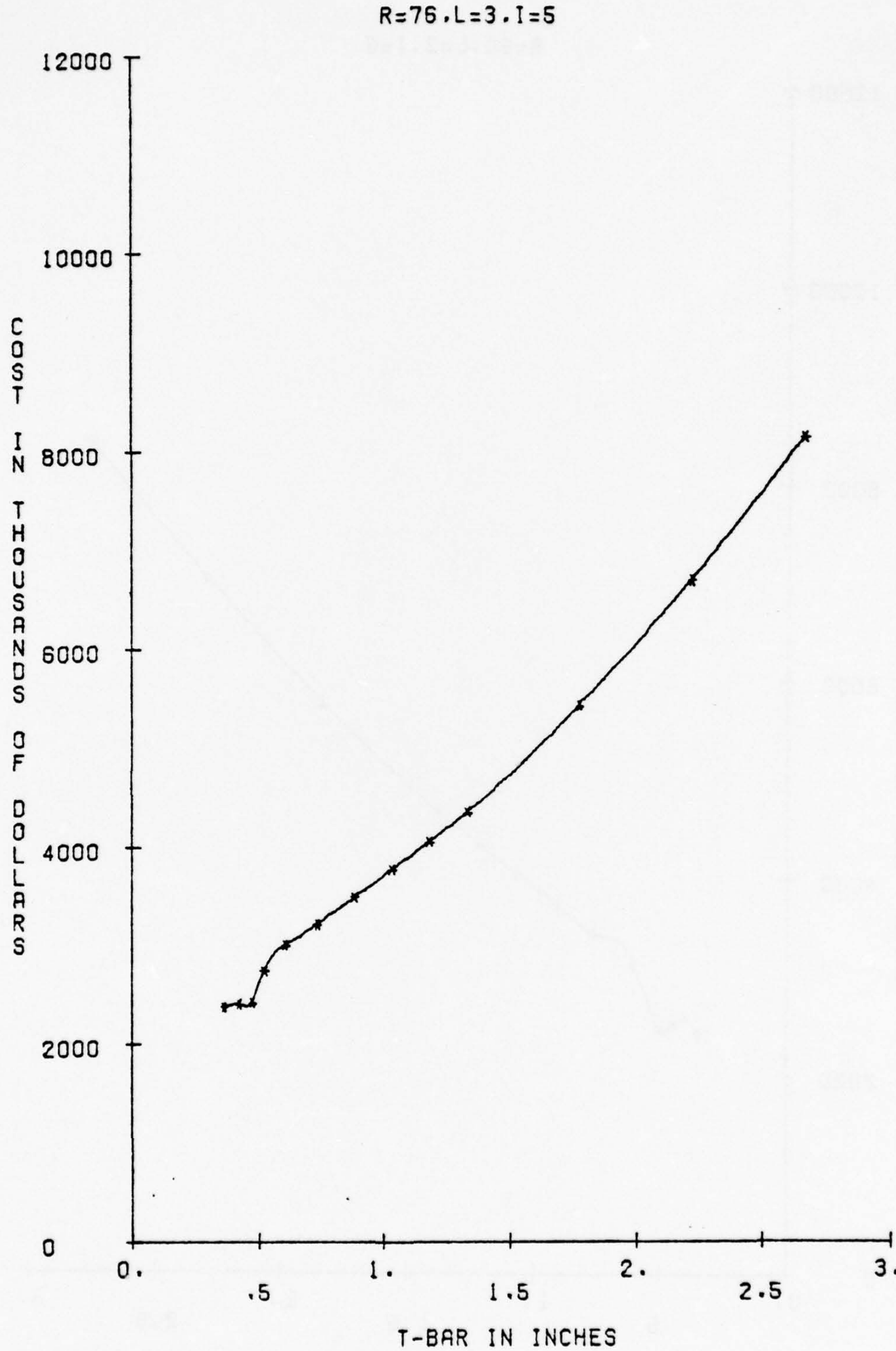

R=46.L=3.I=5
12000
10000
8000
6000
4000
2000
0
COST IN THOUSANDS OF DOLLARS
0.
.5
1.
1.5
2.
2.5
3.
T-BAR IN INCHES

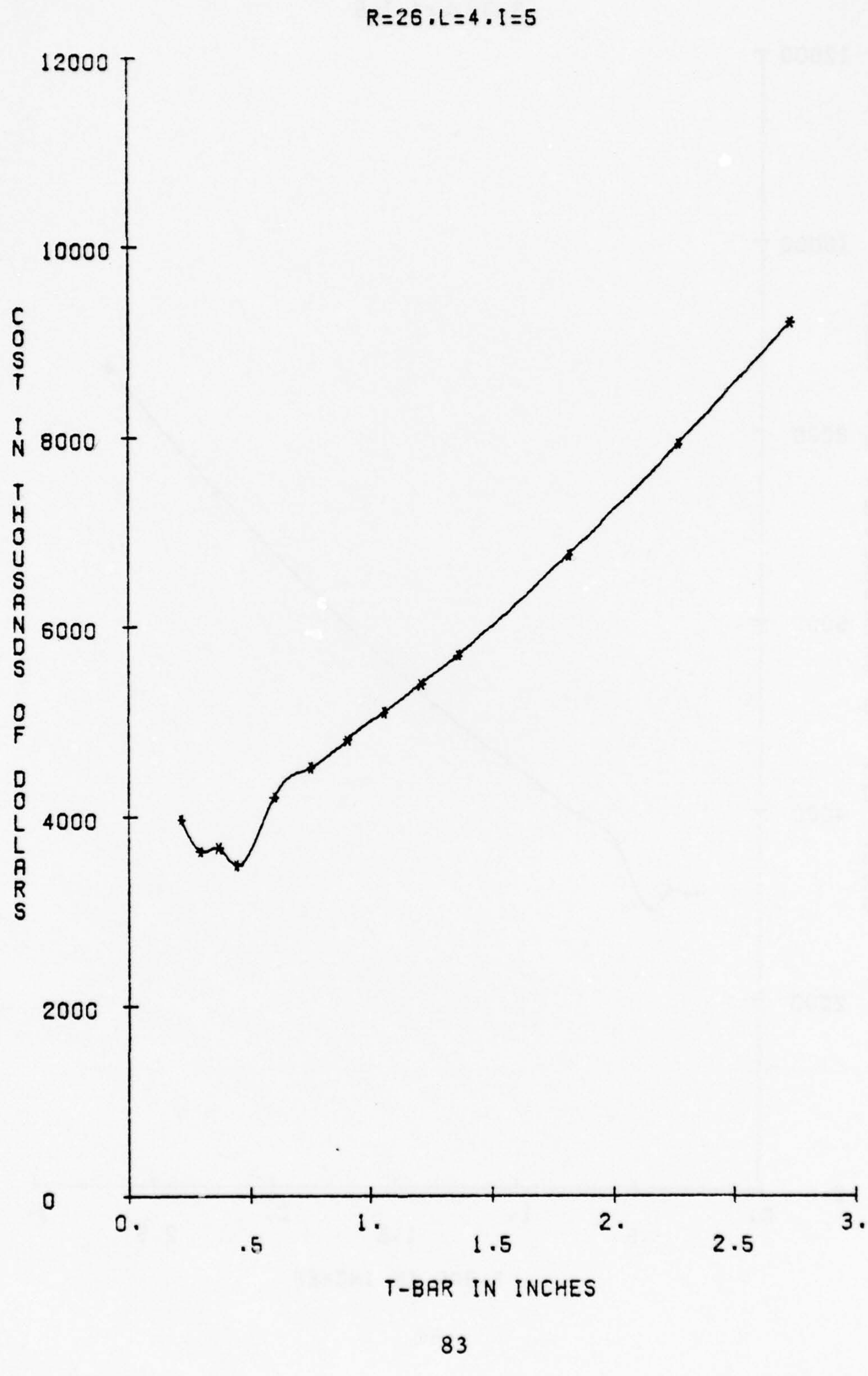


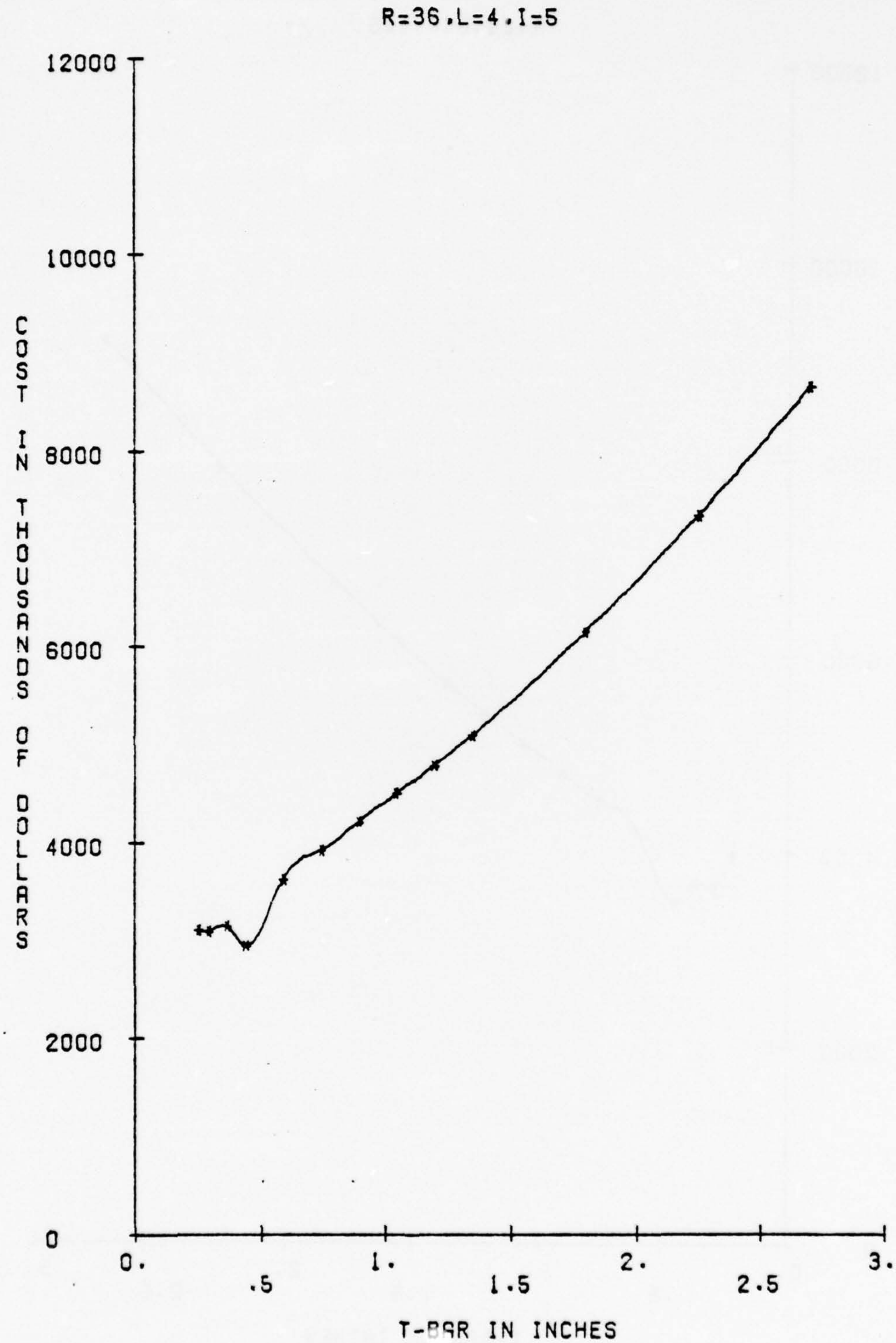
R=56.L=3.I=5
12000
10000
8000
6000
4000
2000
0
COST IN THOUSANDS OF DOLLARS
0.
.5
1.
1.5
2.
2.5
3.
T-BAR IN INCHES

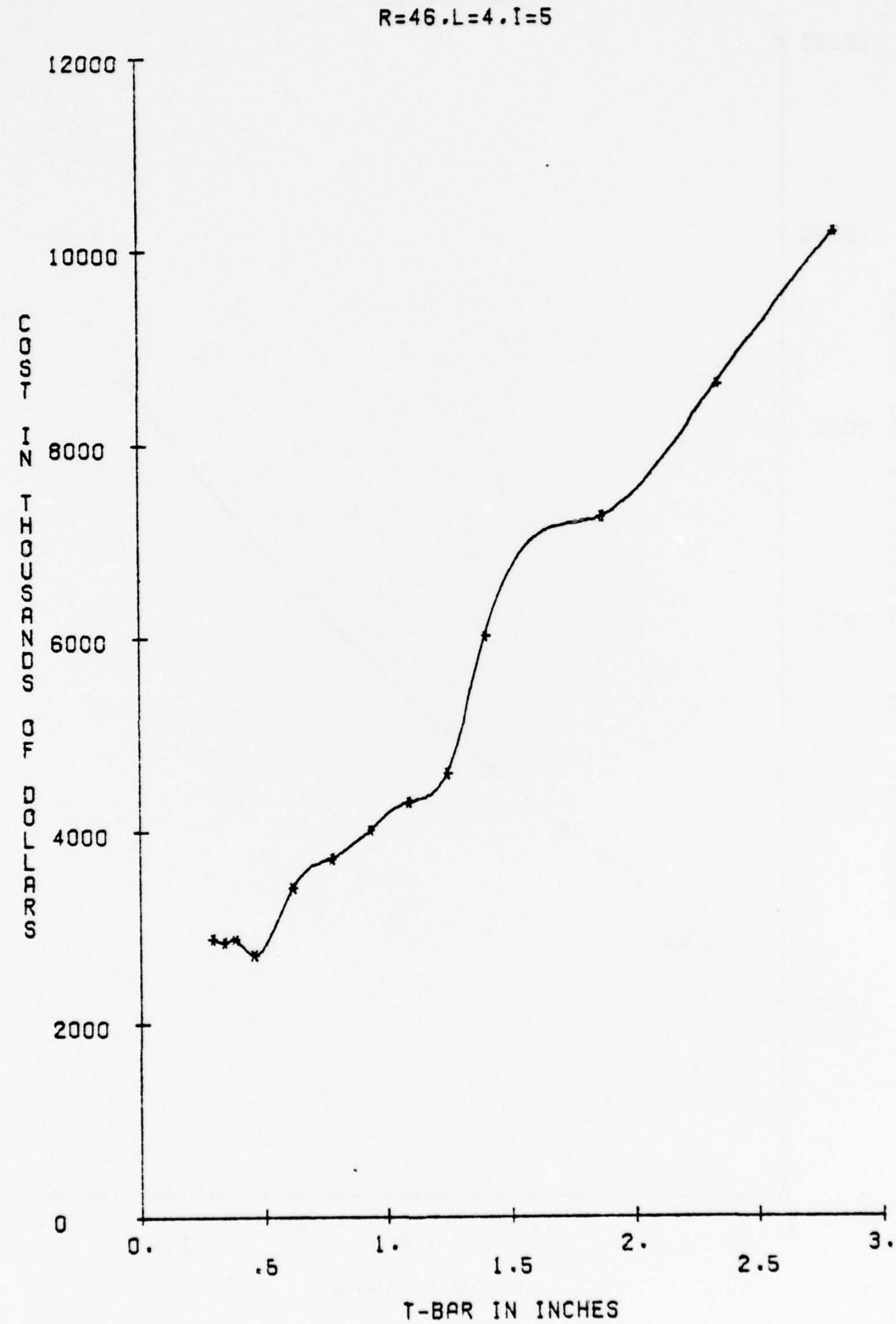
R=66,L=3,I=5


12000
10000
8000
6000
4000
2000
0
COST IN THOUSANDS OF DOLLARS
0.
.5
1.
1.5
2.
2.5
3.
T-BAR IN INCHES

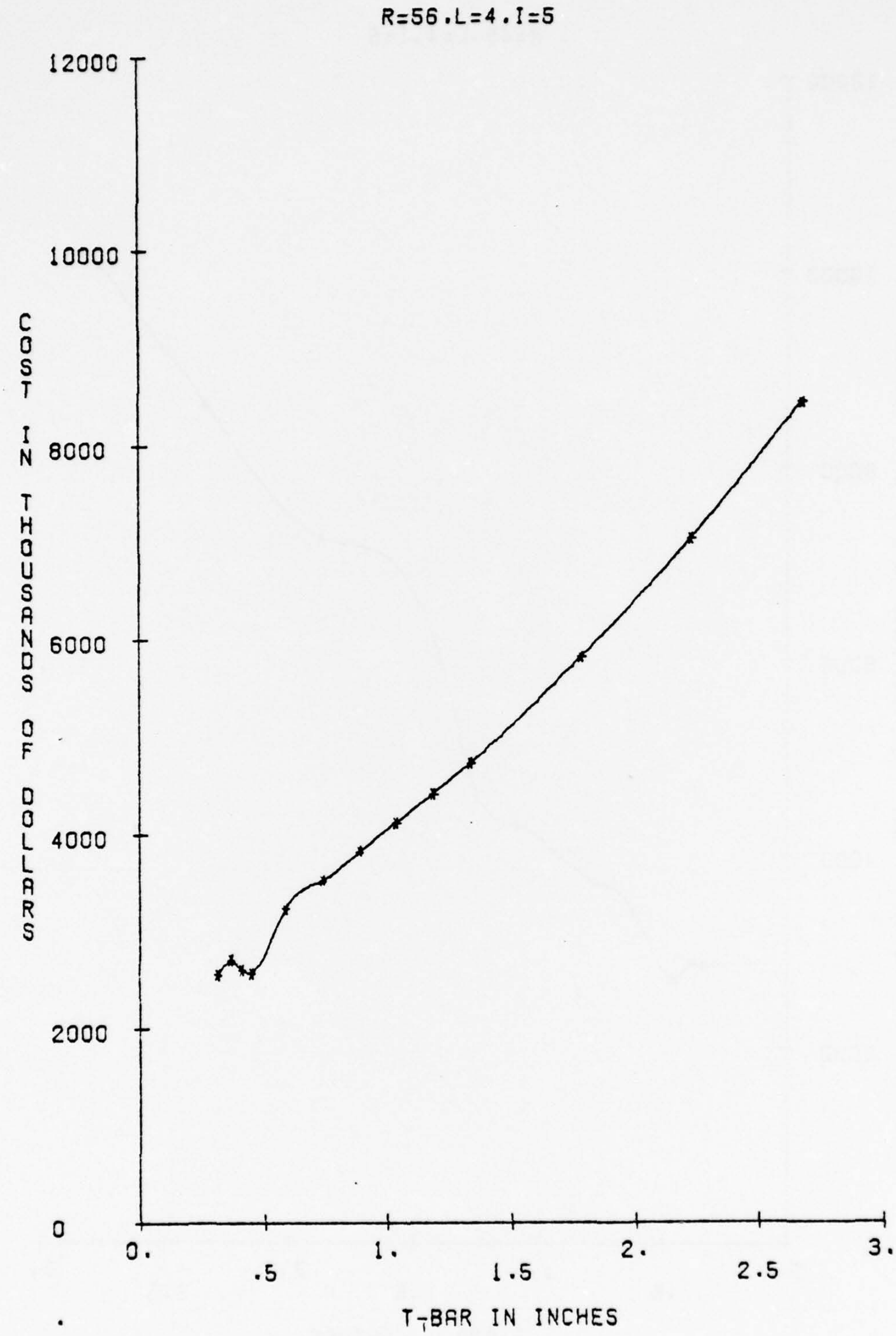

R=76.L=3.I=5
12000
10000
8000
6000
4000
2000
0
C O S T I N T H O U S A N D S O F D O L L A R S
0.
.5
1.
1.5
2.
2.5
3.
T-BAR IN INCHES

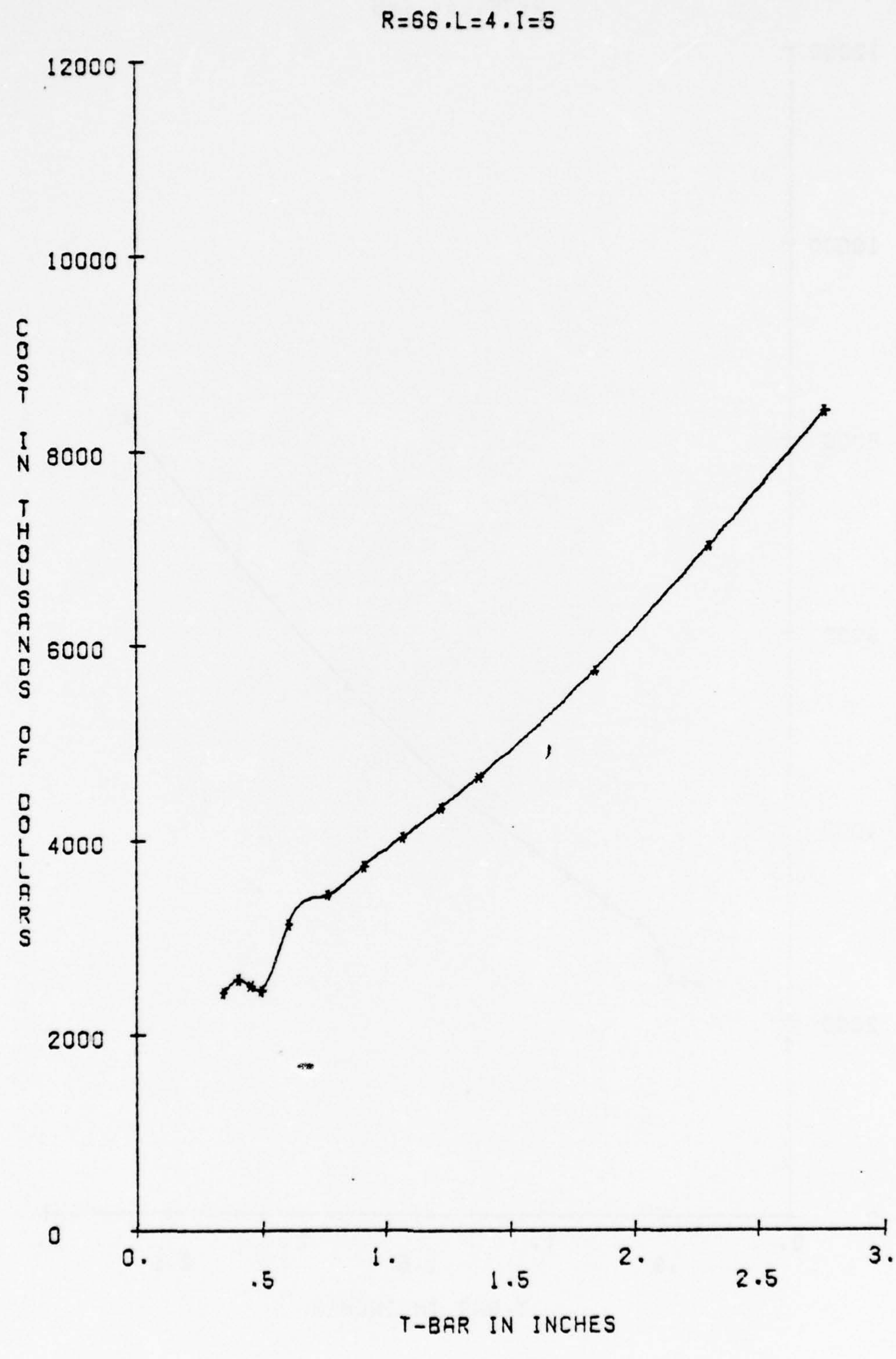

R=26.L=4.I=5
12000
10000
8000
6000
4000
2000
0
COST IN THOUSANDS OF DOLLARS
0.
.5
1.
1.5
2.
2.5
3.
T-BAR IN INCHES

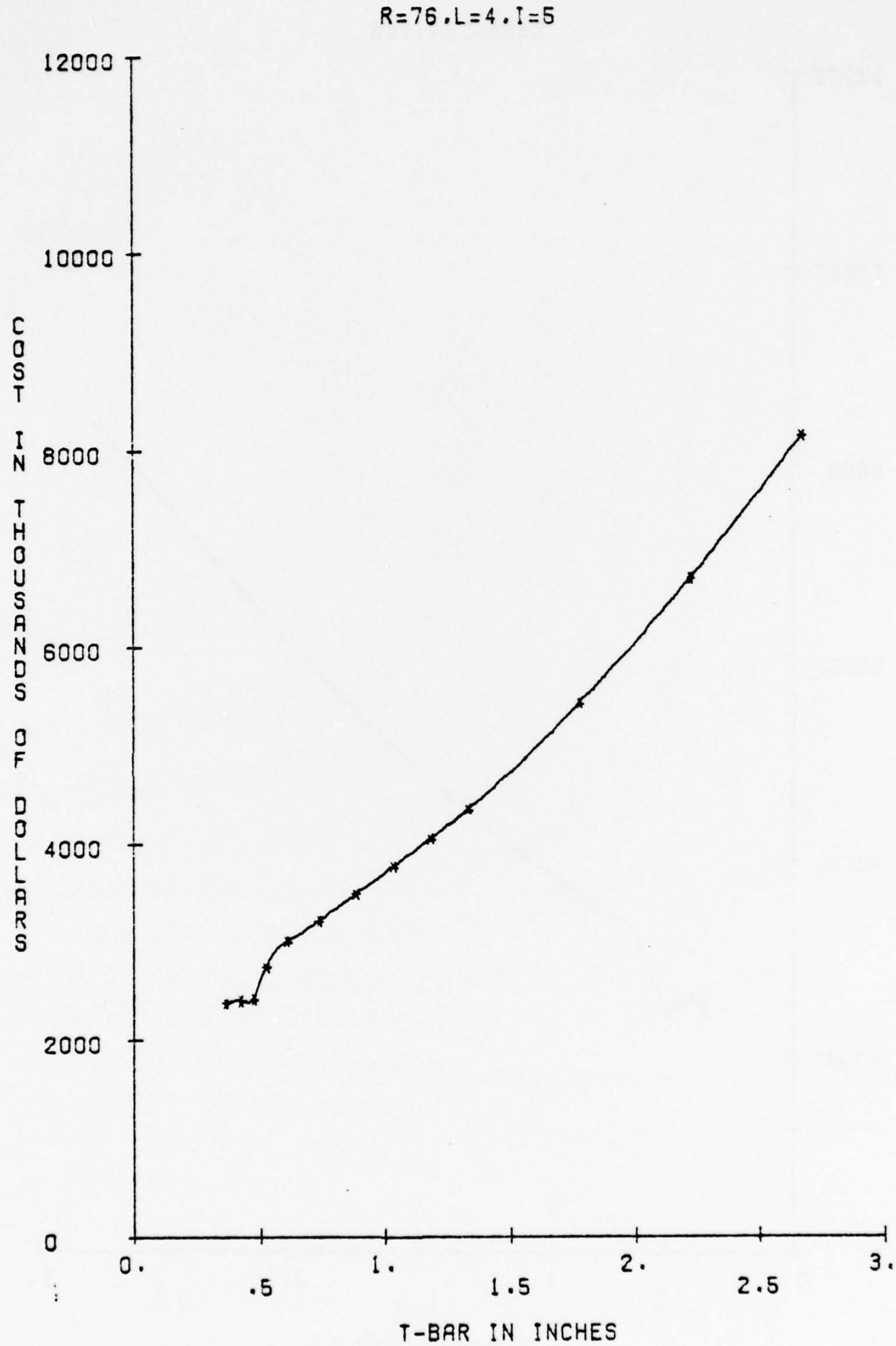

R=36,L=4,I=5
12000
10000
8000
6000
4000
2000
0
COST IN THOUSANDS OF DOLLARS
0.
.5
1.
1.5
2.
2.5
3.
T-BAR IN INCHES



R=46.L=4.I=5
12000
10000
8000
6000
4000
2000
0
COST IN THOUSANDS OF DOLLARS
0.
.5
1.
1.5
2.
2.5
3.
T-BAR IN INCHES

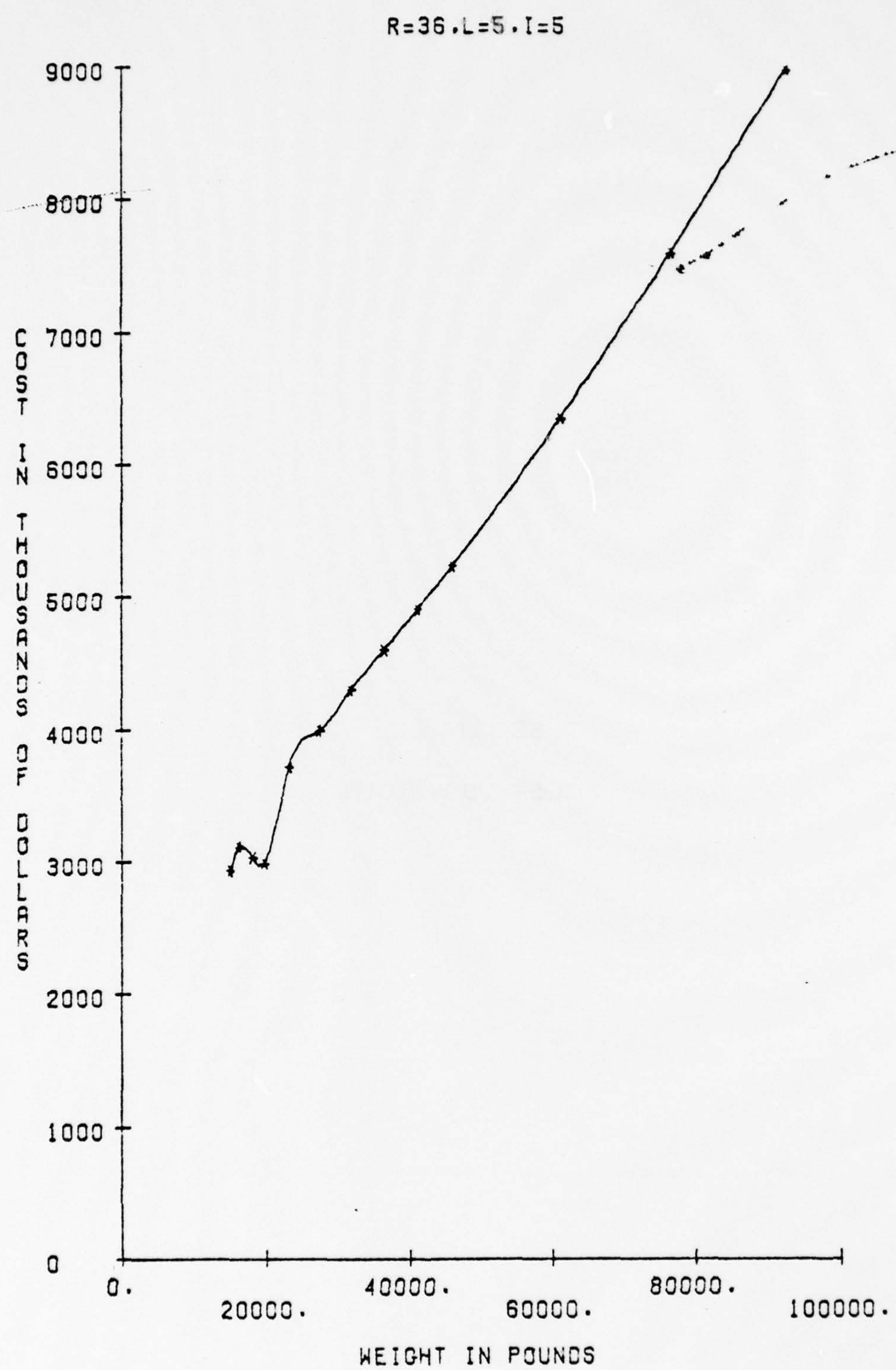

R=56.L=4.I=5
12000
10000
8000
6000
4000
2000
0
COST IN THOUSANDS OF DOLLARS
0.
.5
1.
1.5
2.
2.5
3.
T-BAR IN INCHES

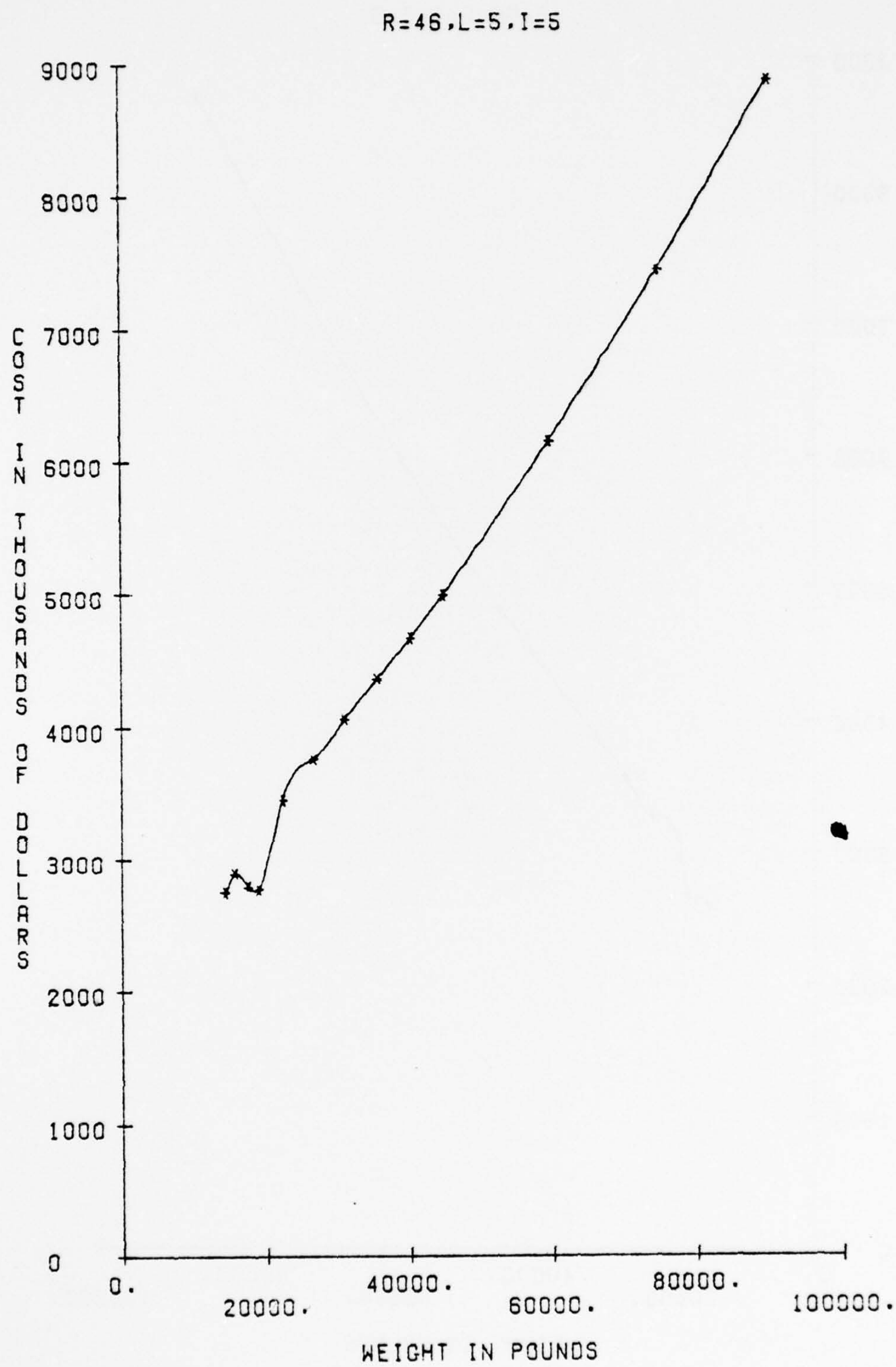

R=66.L=4.I=5
12000
10000
8000
6000
4000
2000
0
COST IN THOUSANDS OF DOLLARS
0.
.5
1.
1.5
2.
2.5
3.
T-BAR IN INCHES

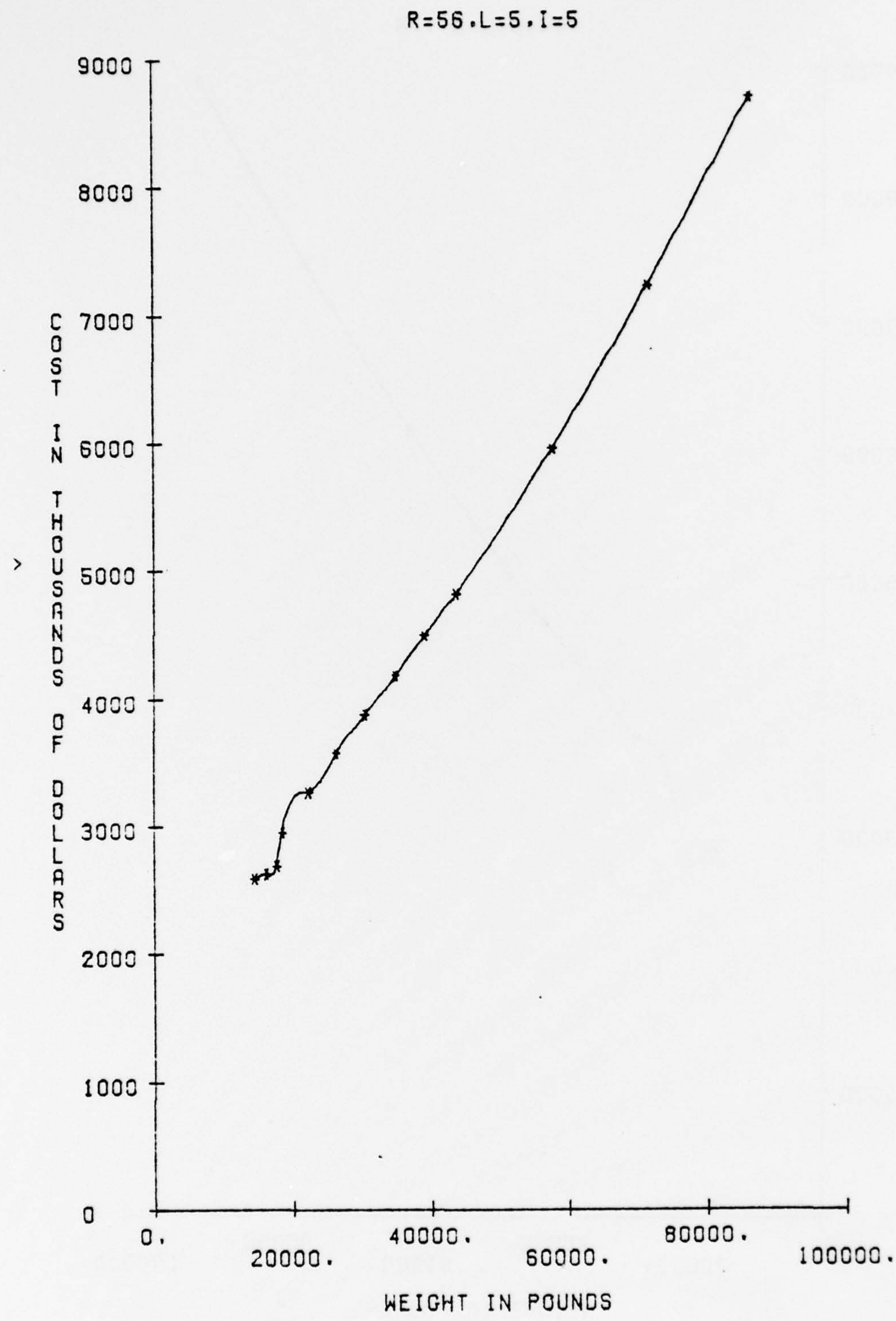

R=76.L=4.I=5
12000
10000
8000
6000
4000
2000
0
COST IN THOUSANDS OF DOLLARS
0.
.5
1.
1.5
2.
2.5
3.
T-BAR IN INCHES

SECTION II

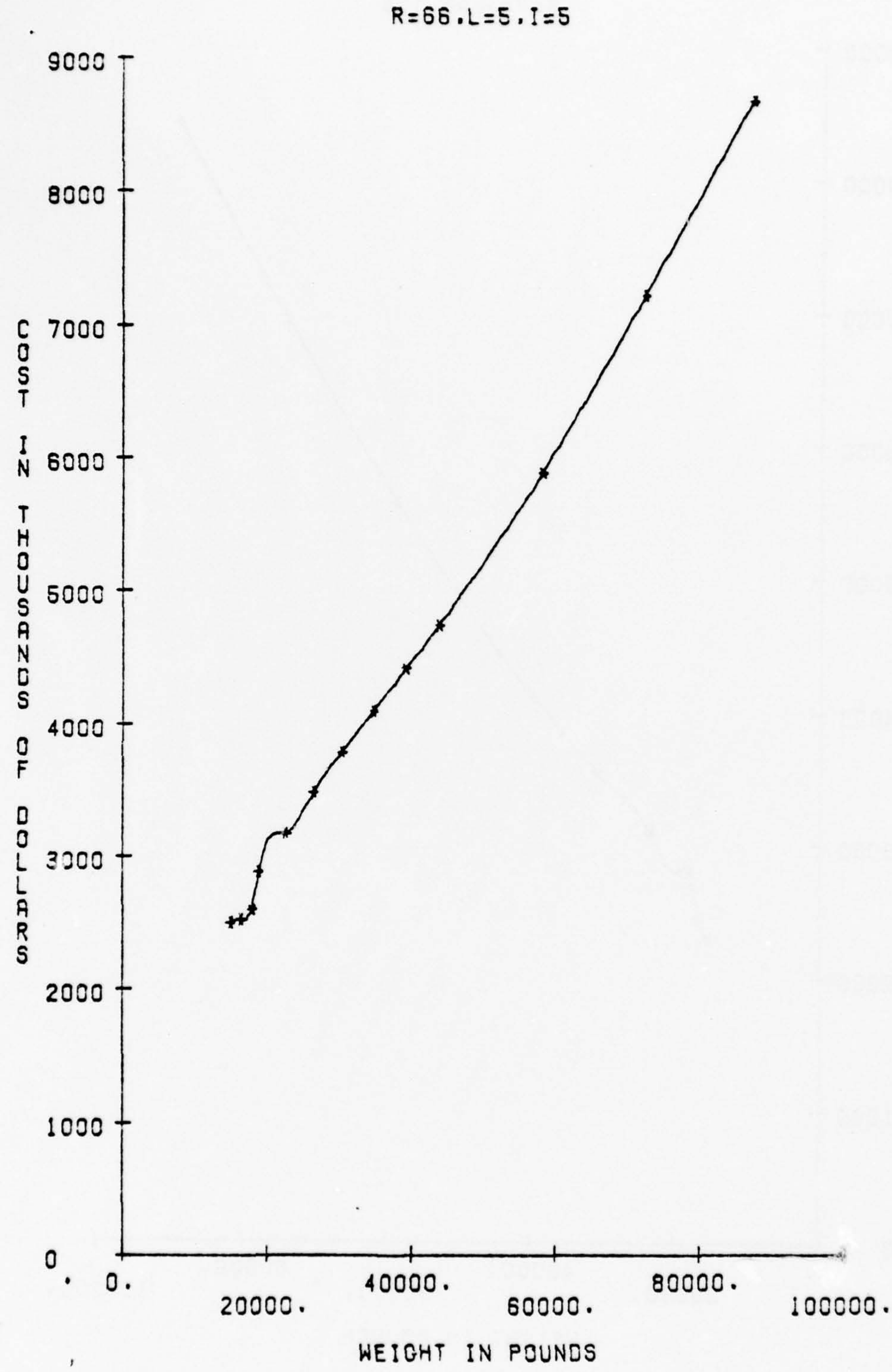
COST VS WEIGHT


R=36.L=5.I=5
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
COST IN THOUSANDS OF DOLLARS
0.
20000.
40000.
60000.
80000.
100000.
WEIGHT IN POUNDS

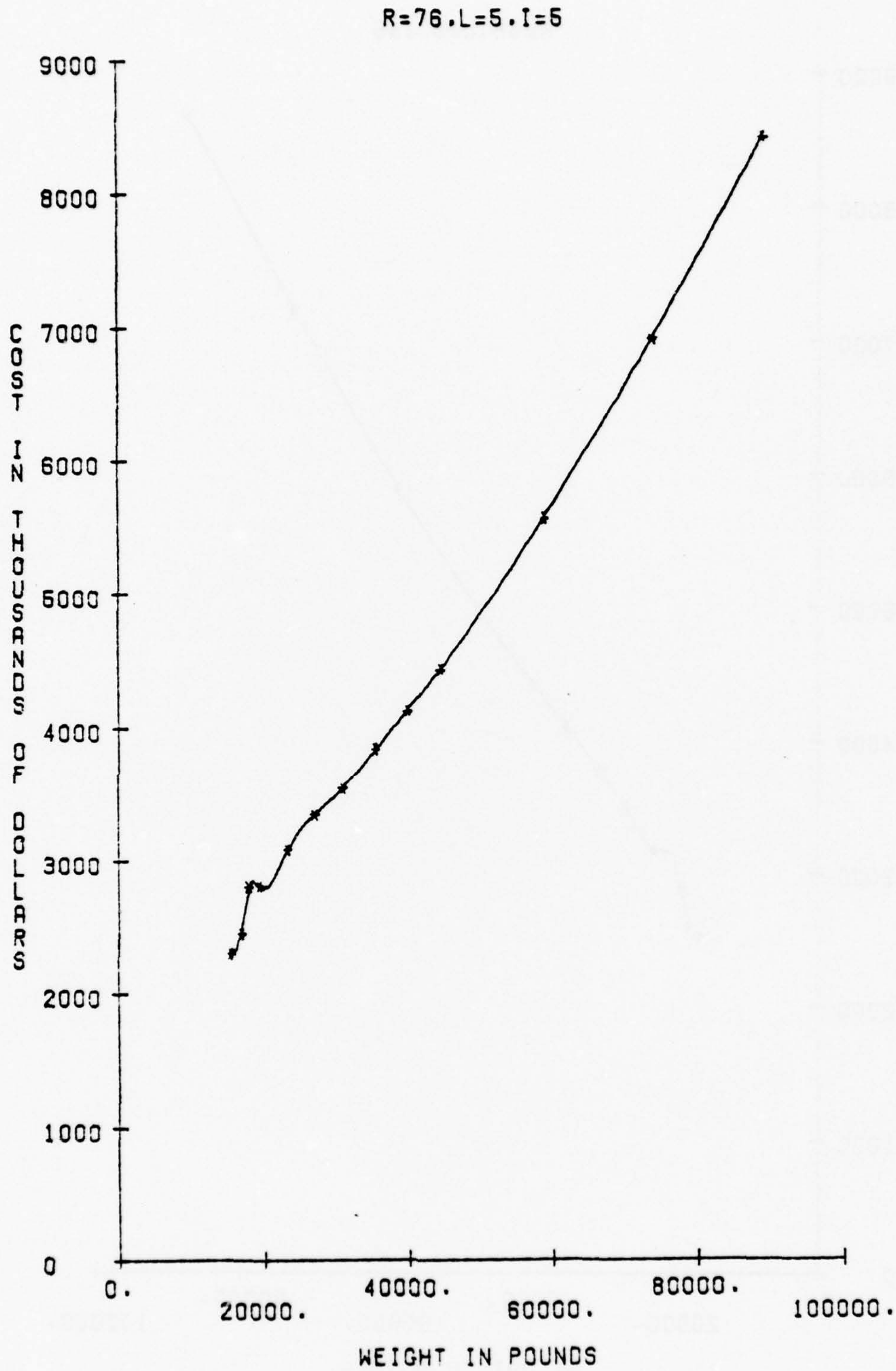

R=46,L=5,I=5
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
COST IN THOUSANDS OF DOLLARS
0.
20000.
40000.
60000.
80000.
100000.
WEIGHT IN POUNDS

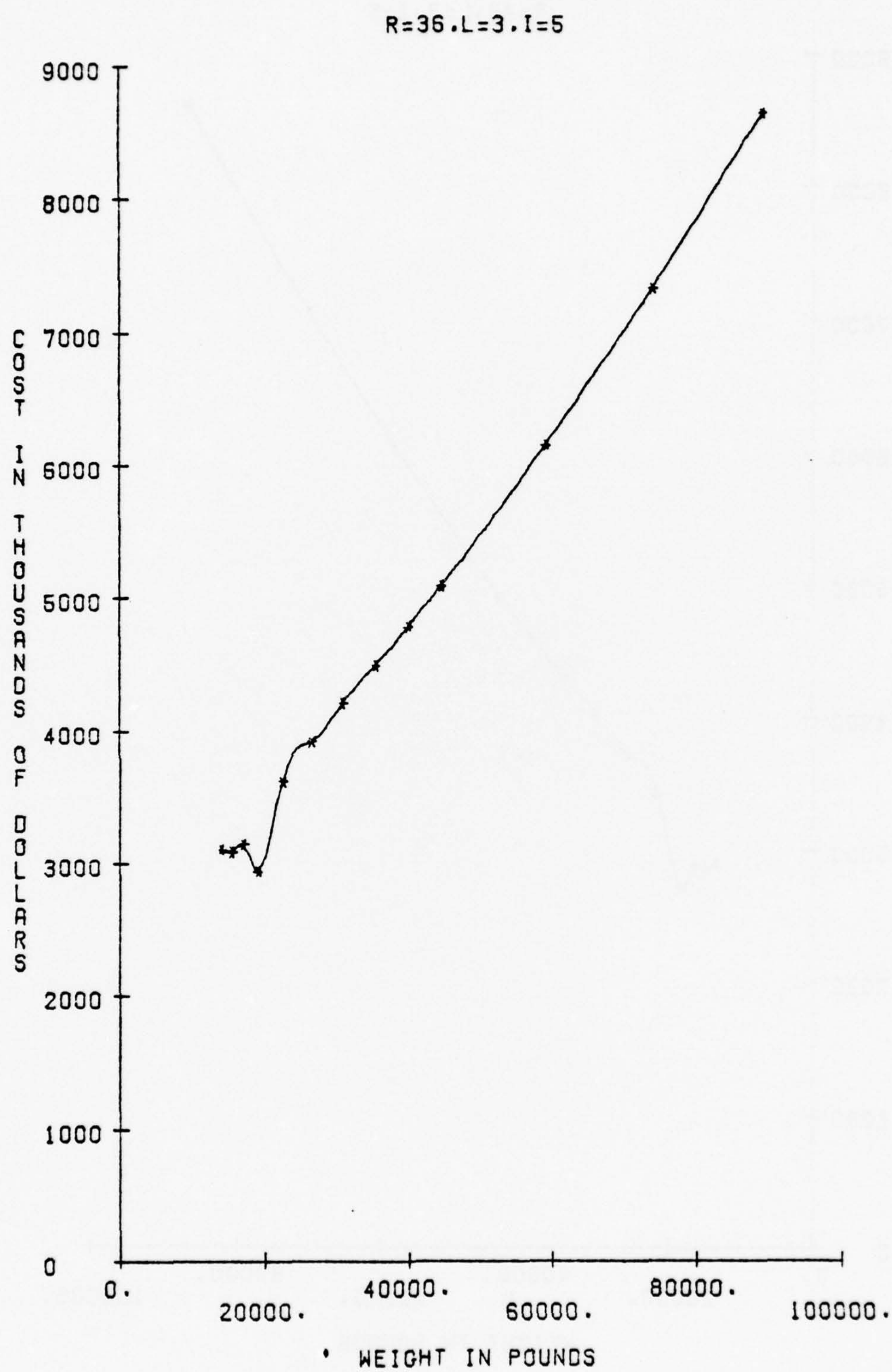


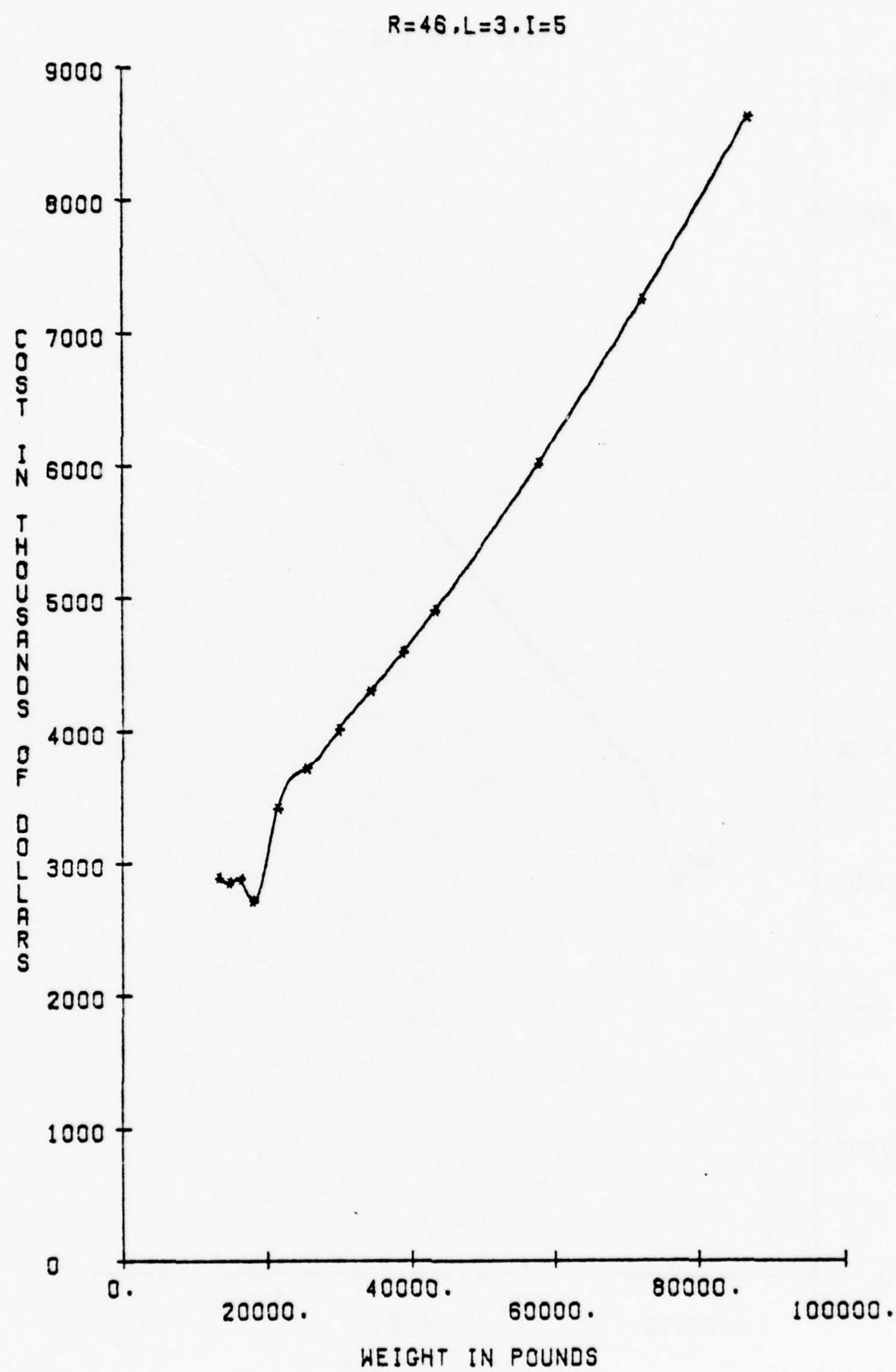
R=56.L=5.I=5
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
COST IN THOUSANDS OF DOLLARS
0.
20000.
40000.
60000.
80000.
100000.
WEIGHT IN POUNDS



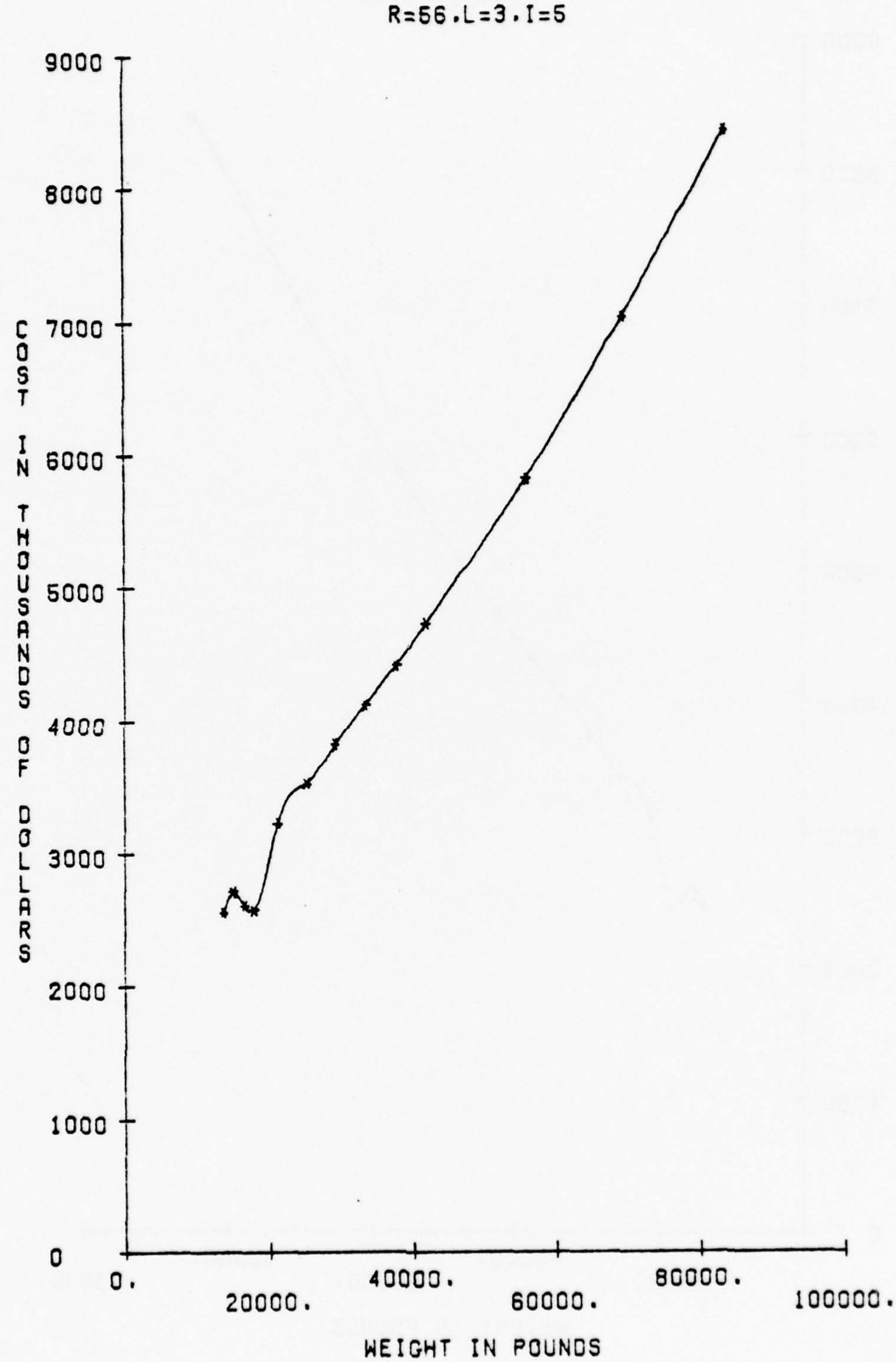
R=66.L=5.I=5
COST IN THOUSANDS OF DOLLARS
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0.
20000.
40000.
60000.
80000.
100000.
WEIGHT IN POUNDS

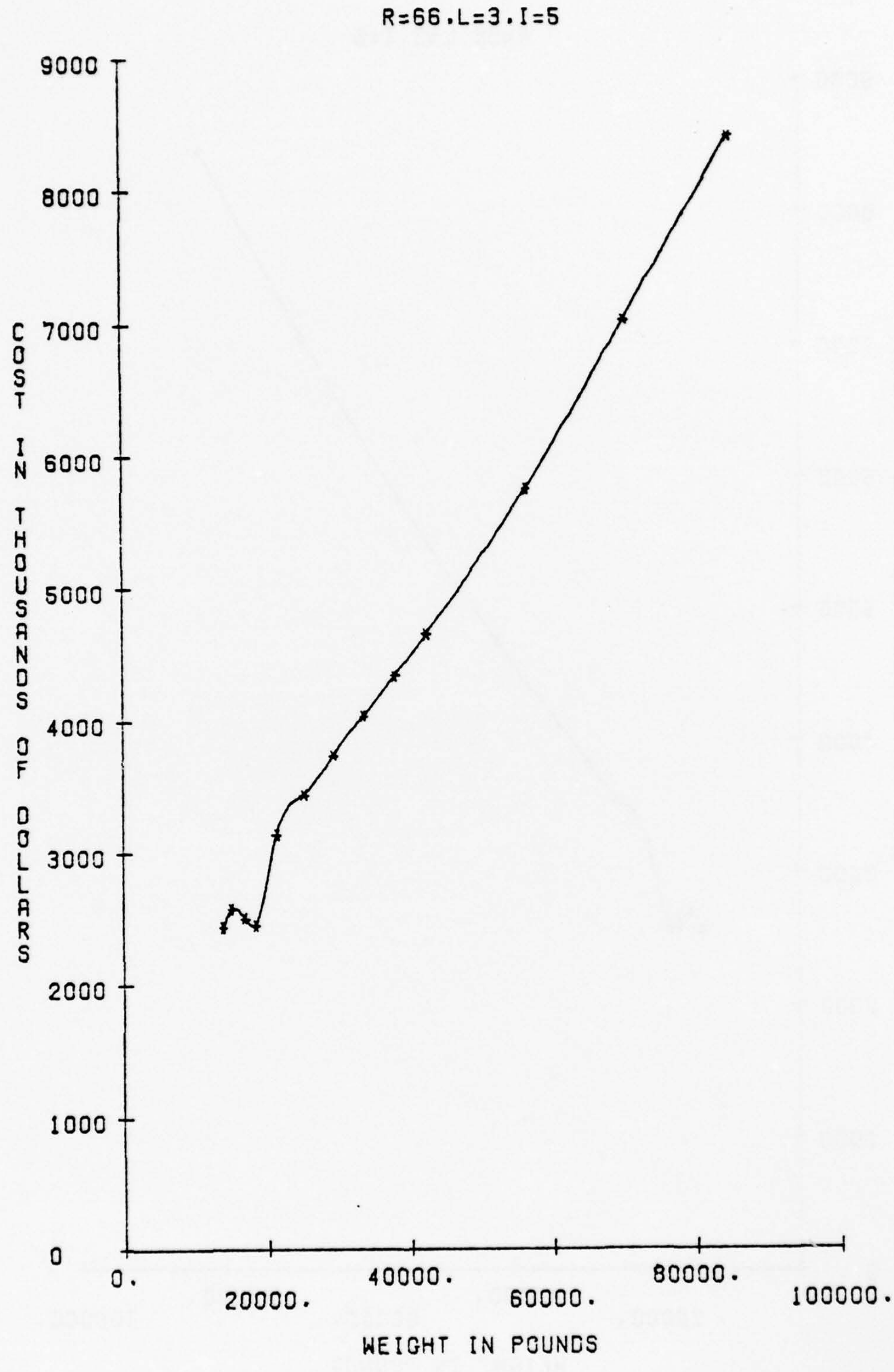

R=76.L=5.I=5
COST IN THOUSANDS OF DOLLARS
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0.
20000.
40000.
60000.
80000.
100000.
WEIGHT IN POUNDS


R=36.L=3.I=5
COST IN THOUSANDS OF DOLLARS
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0.
20000.
40000.
60000.
80000.
100000.
WEIGHT IN POUNDS

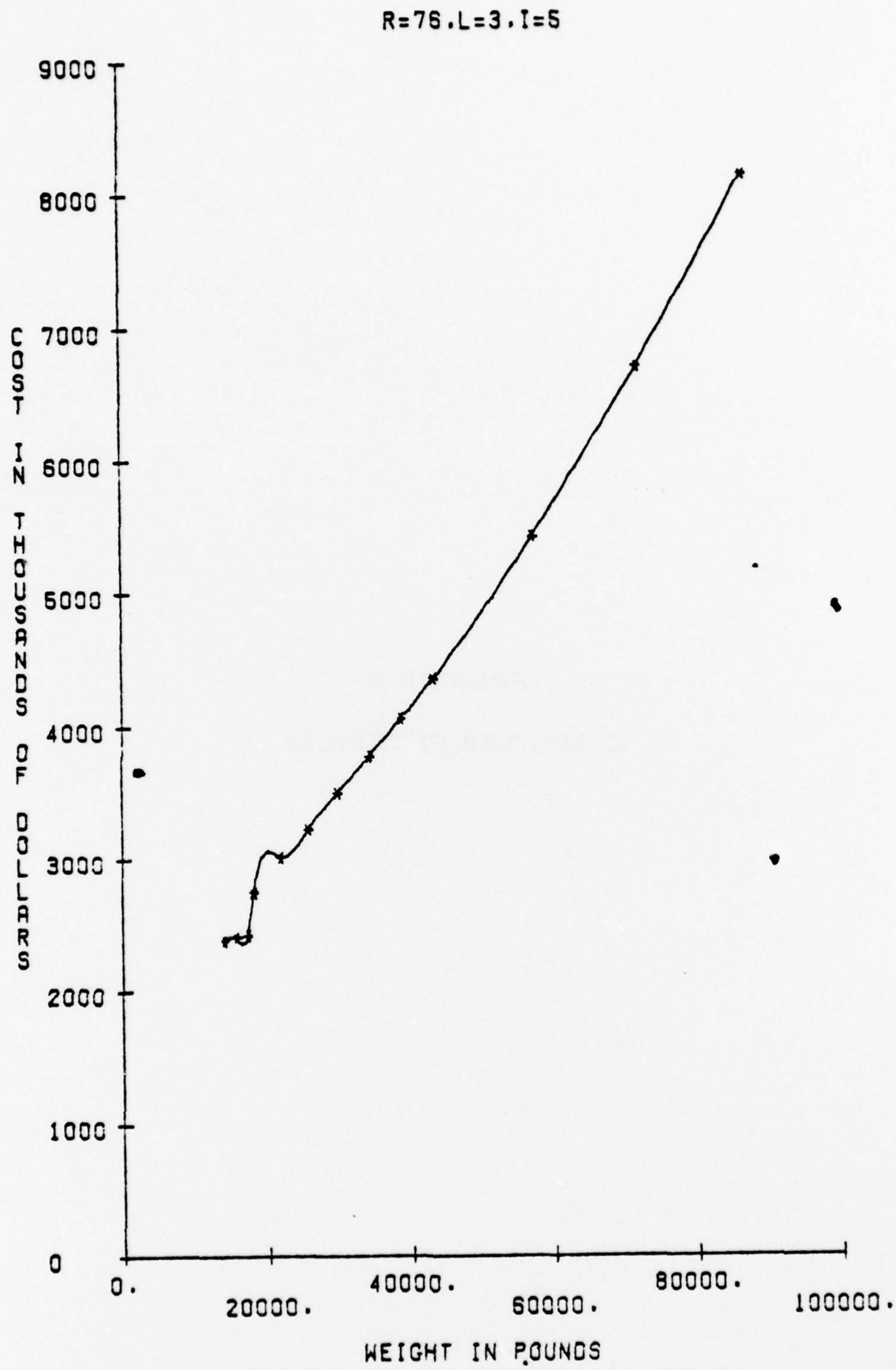


R=46,L=3,I=5
COST IN THOUSANDS OF DOLLARS
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0.
20000.
40000.
60000.
80000.
100000.
WEIGHT IN POUNDS


R=56.L=3.I=5
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
COST IN THOUSANDS OF DOLLARS
0.
20000.
40000.
60000.
80000.
100000.
WEIGHT IN POUNDS



R=66.L=3.I=5
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
COST IN THOUSANDS OF DOLLARS
0.
20000.
40000.
60000.
80000.
100000.
WEIGHT IN POUNDS


R=76.L=3.I=5
COST IN THOUSANDS OF DOLLARS
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0.
20000.
40000.
60000.
80000.
100000.
WEIGHT IN POUNDS

APPENDIX F

COMPUTER PROGRAMS

Multiple Linear Regression

```
10##S,R(SL) :,8,16;;,16
20$:IDENT:WP1191,CHRISTENSEN & EVANS, 77A
30$:SELECT:SPSS/SPSS
40RUN NAME;THESIS PROJECT
50VARIABLE LIST;R,L5,L1,L3,I5,I3,U,T,C,W
60VAR LABELS;R,RIB SPACING/
70;L5,SEPARATE JAY/
80;L1,INTEGRAL BLADE/
90;L3,INTEGRAL ZEE/
100;I5,ALUMINUM/
110;I3,TITANIUM/
120;U,LOAD/
130;T,T-BAR/
140;C,COST/
150;W,WEIGHT
160INPUT FORMAT;FREEFIELD
170INPUT MEDIUM;CARD
180N OF CASES;312
190REGRESSION;VARIABLES=R,L5,L1,L3,U,T,C,W/
200;REGRESSION=C WITH R,L5,L1,L3,U,T,W(1) RESID=0
210STATISTICS;2,6,7
220READ INPUT DATA
230$:SELECTA:77A57/THEDATA
240REGRESSION;VARIABLES=C,W/
250;REGRESSION=C WITH W(2) RESID=0
260STATISTICS;6,7
270REGRESSION;VARIABLES=C,T/
280;REGRESSION=C WITH T(2) RESID=0
290STATISTICS;6,7
300REGRESSION;VARIABLES=C,L5,L1,L3/
310;REGRESSION=C WITH L5,L1,L3(1) RESID=0
320STATISTICS;6,7
330FINISH
340$:ENDJOB
```

Significant MLR and Partial Correlation

```
10##S,R(SL) :,8,16;;,16
20$:IDENT:WP1191,CHRISTENSEN & EVANS, 77A
30$:SELECT:SPSS/SPSS
40RUN NAME;THESIS PROJECT - REGR. &  CORR.
50VARIABLE LIST;R,L5,L1,L3,I5,I3,U,T,C,W
60VAR LABELS;R,RIB SPACING/
70;L5,SEPARATE JAY/
80;L1,INTEGRAL BLADE/
90;L3,INTEGRAL ZEE/
100;I5,ALUMINUM/
110;I3,TITANIUM/
120;U,LOAD/
130;T,T-BAR/
140;C,COST/
150;W,WEIGHT
160INPUT FORMAT;FREEFIELD
170INPUT MEDIUM;CARD
180N OF CASES;312
190REGRESSION;VARIABLES=R,L5,L1,L3,U,C,W/
200;REGRESSION=C WITH R,L5,L1,L3,U,W(1) RESID=0
210STATISTICS;2,6,7
220READ INPUT DATA
230S:SELECTA:77A57/THEDATA
240REGRESSION;VARIABLES=R,L5,L1,L3,U,T,C/
250;REGRESSION=C WITH R,L5,L1,L3,U,T(1) RESID=0
260STATISTICS;2,6,7
270REGRESSION;VARIABLES=R,L1,C,W/
280;REGRESSION=C WITH R.L1,W(1) RESID=0
290STATISTICS;2,6,7
300PARTIAL CORR;C WITH R,L5,L1,L3,U,T,W BY
310;R,L5,L1,L3,U,T,W(1,2)
320STATISTICS;1
330FINISH
340$:ENDJOB
```

Plots of Cost Versus T-bar

```
10##NORM,R(SL)
20$:IDENT:WP1191,AFIT/SLG THESIS PLOTS - 77A
30$:MSG2:1,SEND PLOT TAPE TO PLOTTER (G012B,WP1191)
40$:OPTION:FORTRAN,NOMAP
50$:FORTY:NFORM,NLNO
60 DIMENSION DUM(7),COUNT(13),X(13),RX(100),RY(100)
70 CHARACTER LABEL*72
80 CALL USTART
90 CALL UDIMEN(12.,34.,"CHRISTENSEN & EVANS THESIS\")
100 10 DO 500 MM=1,3
110 DO 5 J=1,13
120 READ(16,1010,END=999)DUM,COUNT(J),X(J)
130 X(J)=X(J)/1000.
140 1010 FORMAT(V)
150 5 CONTINUE
160 YST=(MM-1)*11.
170 YEND=YST+11.
180 CALL UPSET("PRECISION",6.)
190 CALL USET("SMALL")
200 CALL UDAREA(0.,8.5,YST,YEND)
210 CALL UOUTLN
220 CALL UDAREA(1.5,7.,YST+1.,YEND-1.5)
230 CALL USET("XBOTH")
240 CALL USET("YBOTH")
250 CALL UPSET("XLABEL","T-BAR IN INCHES\")
260 CALL UPSET("YLABEL","COST IN THOUSANDS OF DOLLARS\")
270 CALL USET("NOLINE")
280 CALL USET("OWNSCALE")
290 CALL UWINDO(0.,3.,0.,12000.)
300 CALL UPSET("TICX",.5)
310 CALL UPSET("TICY",2000.)
320 CALL UPLOT1(COUNT,X,13.)
330 CALL USET("N*")
340 CALL USET("SOFT")
350 CALL UDOIT("SETSOFT")
360 CALL UMOVE(COUNT(1),X(1))
370 DO 101 J=1,13
380 101 CALL UPEN(COUNT(J),X(J))
390 CALL USET("HARDWARE")
400 CALL USPLIN(COUNT,X,13.,RX,RY,100.)
410 CALL USET("LINE")
420 CALL UMOVE(RX(1),RY(1))
430 DO 100 J=1,100
440 100 CALL UPEN(RX(J),RY(J))
450 READ(17,902)LABEL
```

```
902 FORMAT(A72)
CALL USET("DEVICE")
CALL UMOVE(4.25,YEND-1.5)
CALL UDOIT("UP01")
CALL UDOIT("BS06")
CALL UPRNT1(LABEL,"TEXT")
CALL USET("VIRTUAL")
500 CONTINUE
CALL UERASE
GO TO 10
999 CALL UEND
STOP
END
$:LIBRARY:A1,A2,A3,A4
$:EXECUTE
$:LIMITS:15,40K
$:PRMFL:A1,R,R,GRAPHICS.LIB/GCS/GCS3.0
$:PRMFL:A2,R,R,GRAPHICS.LIB/GCS/CALC3.0
$:PRMFL:A3,R,R,AF.LIB/CALLIB
$:PRMFL:A4,R,R,GRADLIB/BATCH
$:FFILE:27,FIXLNG/80,BUFSIZ/81
$:TAPE:27,X1D,,,,PLOT-TAPE/WR
$:DATA:16
$:SELECTA:77A57/THEDATA
$:DATA:17
$:SELECTA:77A57/THESIS04
$:ENDJOB
```

Plots of Cost Versus Weight

```
##NORM,R(SL)
$:IDENT:WP1191,AFIT/SLG THESIS PLOTS - STUDENTS 77A
$:MSG2:1,SEND PLOT TAPE TO PLOTTER (G012B,WP1191)
$:OPTION:FORTRAN,NOMAP
$:FORTY:NFORM,NLNO
DIMENSION DUM(8),X(13),COUNT(13),RX(100),RY(100)
CHARACTER LABEL*72
CALL USTART
CALL UDIMEN(12.,34.,"CHRISTENSEN & EVANS THESIS\")
10 DO 500 MM=1,3
DO 5 J=1,13
READ(16,1010,END=999)DUM,X(J),COUNT(J)
X(J)=X(J)/1000.
1010 FORMAT(V)
5 CONTINUE
YST=(MM-1)*11.
YEND=YST+11.
CALL UPSET("PRECISION",6.)
CALL USET("SMALL")
CALL UDAREA(0.,8.5,YST,YEND)
CALL UOUTLN
CALL UDAREA(1.5,7.,YST+1.,YEND-1.5)
CALL USET("XBOTH")
CALL USET("YBOTH")
CALL UPSET("XLABEL","WEIGHT IN POUNDS\")
CALL UPSET("YLABEL","COST IN THOUSANDS OF DOLLARS\")
CALL USET("NOLINE")
CALL UPLOT1(COUNT,X,13.)
CALL USET("N*")
CALL USET("SOFT")
CALL UDOIT("SETSOFT")
CALL UMOVE(COUNT(1),X(1))
DO 101 J=1,13
101 CALL UPEN(COUNT(J),X(J))
CALL USET("HARDWARE")
CALL USPLIN(COUNT,X,13.,RX,RY,100.)
CALL USET("LINE")
CALL UMOVE(RX(1),RY(1))
DO 100 J=1,100
100 CALL UPEN(RX(J),RY(J))
READ(17,902)LABEL
902 FORMAT(A72)
CALL USET("DEVICE")
CALL UMOVE(4.25,YEND-1.5)
CALL UDOIT("UP01")
```

```
460 CALL UDOIT("BS06")
470 CALL UPRNT1(LABEL,"TEXT")
480 CALL USET("VIRTUAL")
490 500 CONTINUE
500 CALL UERASE
510 GO TO 10
520 999 CALL UEND
530 STOP
540 END
550$:LIBRARY:A1,A2,A3,A4
560$:EXECUTE
570$:LIMITS:15,40K
580$:PRMFL:A1,R,R,GRAPHICS.LIB/GCS/GCS3.0
590$:PRMFL:A2,R,R,GRAPHICS.LIB/GCS/CALC3.0
600$:PRMFL:A3,R,R,AF.LIB/CALLIB
610$:PRMFL:A4,R,R,GRADLIB/BATCH
620$:FFILE:27,FIXLNG/80,BUFSIZ/81
630$:TAPE:27,X1D,,,,PLOT-TAPE/WR
640$:DATA:16
650$:SELECTA:77A57/THEDATA
660$:DATA:17
670$:SELECTA:77A57/THESIS04
680$:ENDJOB
```

SELECTED BIBLIOGRAPHY

A. REFERENCES CITED

1. Blanton, Major General Charles C., USAF. Director of the Budget. "The Air Force Since 1952." Address to University of Maryland Air Force ROTC Commissioning Ceremony, 15 May 1976. As reprinted in Supplement to the Air Force Policy Letter For Commanders, No. 9-1976, pp. 25-29.

2. Busbe, Major Walter, USA. Instructor, Department of Logistics, U.S. Army Command and General Staff College. Lecture to Command General Staff students, Fort Leavenworth KA. 24 March 1976.

3. Clark, Charles T., and Lawrence L. Schkade. Statistical Analysis for Administrative Decisions, 2nd ed. Cincinnati, Ohio: South-Western Publishing Co., 1974.

4. Currie, Doctor Malcom R., and Arthur I. Mendolia. "An Introduction . . . ," Defense Management Journal. September, 1974, p. 1.

5. Heinrich, Major General Frank A., USA. "Design to Cost Requires Common Understanding, Clear Direction," Defense Management Journal, April, 1973, pp. 59-66.

6. Horn, Lieutenant Noel Paul, USN, and Lieutenant Peter Vincent Dabbieri, Jr., USN. "Design to Cost: Concept and Application." Unpublished master's thesis. Naval Postgraduate School, Monterey CA. 1974. AD-A004233.

7. Kendall, Maurice G., and Alan Stuart. The Advanced Theory of Statistics, Vol 2. Inference and Relationships. New York: Hafner Publishing Co., 1967.

8. Lawrence, Captain Frederick, USAF. Instructor in Quantitative Methods, Graduate Education Division, School of Systems and Logistics, Air Force Institute of Technology (AU), Wright-Patterson AFB OH. AFIT course QM 5.32, "Statistics II," Class 1977A. Lectures 4 October--19 November 1976.

9. Levinson, G.S., and others. Cost-Estimating Relationships for Aircraft Airframes. Technical report, R-761-PR, Deputy Chief of Staff, Research and Development (Air Force). 1972. AD-A 012091.

10. Linville, Captain Ray P., USAF, and Lieutenant Warren M. Rose, USAF. "Design-to-Cost: An Examination of Its Use in Weapon System Acquisitions." Unpublished master's thesis, SLSR 31-73B, AFIT/SL, Wright-Patterson AFB OH. 1973. AD 769199.

11. Mueller, Richard. Aerospace Engineer, Cost and Weight Analysis Group, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB OH. Personal interview. 15 October 1976.

12. Murchland, Richard. Chief, Cost Estimating Division, Directorate of Program Control, A-10A System Program Office, Wright-Patterson AFB OH. Personal interview. 10 August 1976.

13. Nelson, Dale. Aerospace Engineer, Program Manager for Vehicle Design Dvaluation Program, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB OH. Personal interviews conducted intermittently from 15 October 1976 to 6 April 1977.

14. Neter, John, and William Wasserman. Applied Linear Statistical Models. Homewood, Illinois: Richard D. Irwin, Inc., 1974.

15. Nie, Norman H., and others. Statistical Package for the Social Sciences, 2nd ed. New York: McGraw-Hill Book Company, 1975.

16. Oman, B. H. Program Manager, Research and Engineering, General Dynamics Convair Aerospace Division. Letter, subject: Develop Manufacturing Cost Methodology for Metallic and Composite Structure Using Detail Part and Assembly Fabrication Processes, to Structures Division, AFFDL, Wright-Patterson AFB OH, undated.

17. Randolph, Major D. David, USAF. Test Manager, Advanced Tanker/Cargo Aircraft Joint Program Office, Air Force Acquisition Logistics Division, Wright-Patterson AFB OH. Personal interview. 29 December 1976.

18. Saas, C. Joseph. Fortran IV Programming and Applications. San Francisco: Holden-Day, Inc., 1974.

19. Talley, M. E. Aerospace Engineer, Preliminary Design, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB OH. Personal interviews conducted intermittently from 3 September 1976 to 17 May 1977.

20. Taylor, Walton R. L. "ASD/Industry Cost Estimating Workshop." Unpublished report, unnumbered, presentation of Boeing Aerospace Company in St. Louis MO. September, 1975.

21. U.S. Department of the Air Force. A Guide for Program Management, AFSC Pamphlet 800-3. Washington: Government Printing Office, 1976.

22. U.S. Department of the Army, the Navy, and the Air Force. Joint Design to Cost Guide. A Conceptual Approach for Major Weapon System Acquisition. AMCP 700-6, NAVMAT P5242, and AFLC/AFSCP 800-19. Washington: Government Printing Office, 1973.

23. U.S. Department of Defense. Acquisition of Major Defense Systems. Directive 5000.1. Washington: Government Printing Office, 1975.

24. ________. Design to Cost. Directive 5000.28. Washington: Government Printing Office, 1975.

25. Webster, A. Merriam. Webster's Third New International Dictionary of the English Language Unabridged. Springfield, Massachusetts, G&C Merriam Company, Publishers, 1965.

26. Wonnacott, Thomas H., and Ronald J. Wonnacott. Introductory Statistics for Business and Economics. New York: John Wiley & Sons, Inc., 1972.

B. RELATED SOURCES

Dunne, Captain William E., USAF. Microeconomic Theory Applied to Parametric Cost Estimation of Aircraft Airframes. Unpublished master's thesis, GOP/SM/75D-3, AFIT/EN. Wright-Patterson AFB OH, 1975. AD-A020210.

Hamer, Major Stephen A., USAF. Problems Encountered in Implementing Design to a Cost in Major Air Force Weapon System Acquisition Programs. Unpublished master's thesis, GSM/SM/73-11, AFIT/EN, Wright-Patterson AFB OH, 1973. AD 769912.

Hockett, J. M., and others. Life Cycle Cost/Design-to-Cost Guidelines. Technical report, ESD-TR-75-77, by MITRE Corp. for Electronics Systems Division, Hanscom AFB MA, 1975. ADB 0069196L.

Kenyon, R. E. Weapon System Costing Methodology for Airframes and Basic Structures, Vol. I. Technical Volume. Technical report, TR-75-44, Air Force Flight Dynamics Laboratory, Advanced Structures Division, Wright-Patterson AFB OH, 1975. ADA 016408.

________. Weapon System Costing Methodology for Airframes and Basic Structures, Vol. II, two parts. Estimating Handbook and User's Manual. Technical report, TR-75-44, Air Force Flight Dynamics Laboratory, Advanced Structures Division, Wright-Patterson AFB OH, 1975. ADA 016409, ADA 016410.

________. Weapon System Costing Methodology for Airframes and Basic Structures, Vol. III. Cost Data Base. Technical report, TR-73-129, Air Force Flight Dynamics Laboratory, Advanced Structures Division, Wright-Patterson AFB OH, 1974.

________. Weapon System Costing Methodology for Airframes and Basic Structures, Vol. IV. Estimating Techniques Handbook. Technical report, TR-73-125, Air Force Flight Dynamics Laboratory, Advanced Structures Division, Wright-Patterson AFB OH, 1974.

Large, Joseph P., Harry G. Campbell, and David Cates. Parametric Equations for Estimating Aircraft Airframe Costs. Technical report, R-1693-1-PA&E, Rand Corp. for Assistant Secretary of Defense (Program Analysis and Evaluation). February 1976. ADA 022086.

Nelson, Captain Eric E., USAF, and Captain William E. Smith, USAF. A Taxonomy of Cost Estimating Characteristics as Applied to an Aircraft Replenishment Spares Model. Unpublished master's thesis, SLSR 01-76A, AFIT/SL, Wright-Patterson AFB OH, 1976.

O'Brien, Captain Patrick W., USAF. Joint Generalized Least Squares Applied to Cost Estimation for Fighter Aircraft. Unpublished master's thesis, GSA/SM/74D-7, AFIT/EN, Wright-Patterson AFB OH, 1974. ADA-A 003354.

Okraski, Henry C., and William F. Pairish, Jr. Acquisition Cost Estimating Using Simulation. Technical memorandum, 75-4, Training Analysis and Evaluation Group, Orlando FL, 1975. AD-A 015624.

Quigley, D. L., and R. E. Reel. Comparison of Military and Commercial Design-to-Cost Aircraft Procurement and Operational Support Practices. Technical report, TR-75-64, AFFDL, Wright-Patterson AFB OH, 1975. ADB 009248.

Smith, Lieutenant Colonel Lee E., USAF. The Impact of Design-to-Cost on Value Engineering and Life Cycle Costing. Unpublished research report, 5425, Air War College, Maxwell AFB AL, 1974. AD 919-238L.